Technological Progress Towards Meeting the 2007 On-Road Heavy-Duty Engine Emission Standards

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Bruce Bertelsen, MECA

Timothy Johnson, Corning Incorporated

Emission Control Industry's Perspective on Technological Progress

- Our Industry Concurs with the Conclusions of EPA's *Highway Diesel Progress Review*
  - The necessary investments are being made by the emission control industry to develop and commercialize the diesel exhaust emission control technologies that will be needed to help meet the 2007 HDE standards
    - Over $1.5 billion invested by 12 MECA companies
  - The technological progress in developing and commercializing diesel particulate filter and NOx adsorber technology is on track to be ready in 2007 and 2010

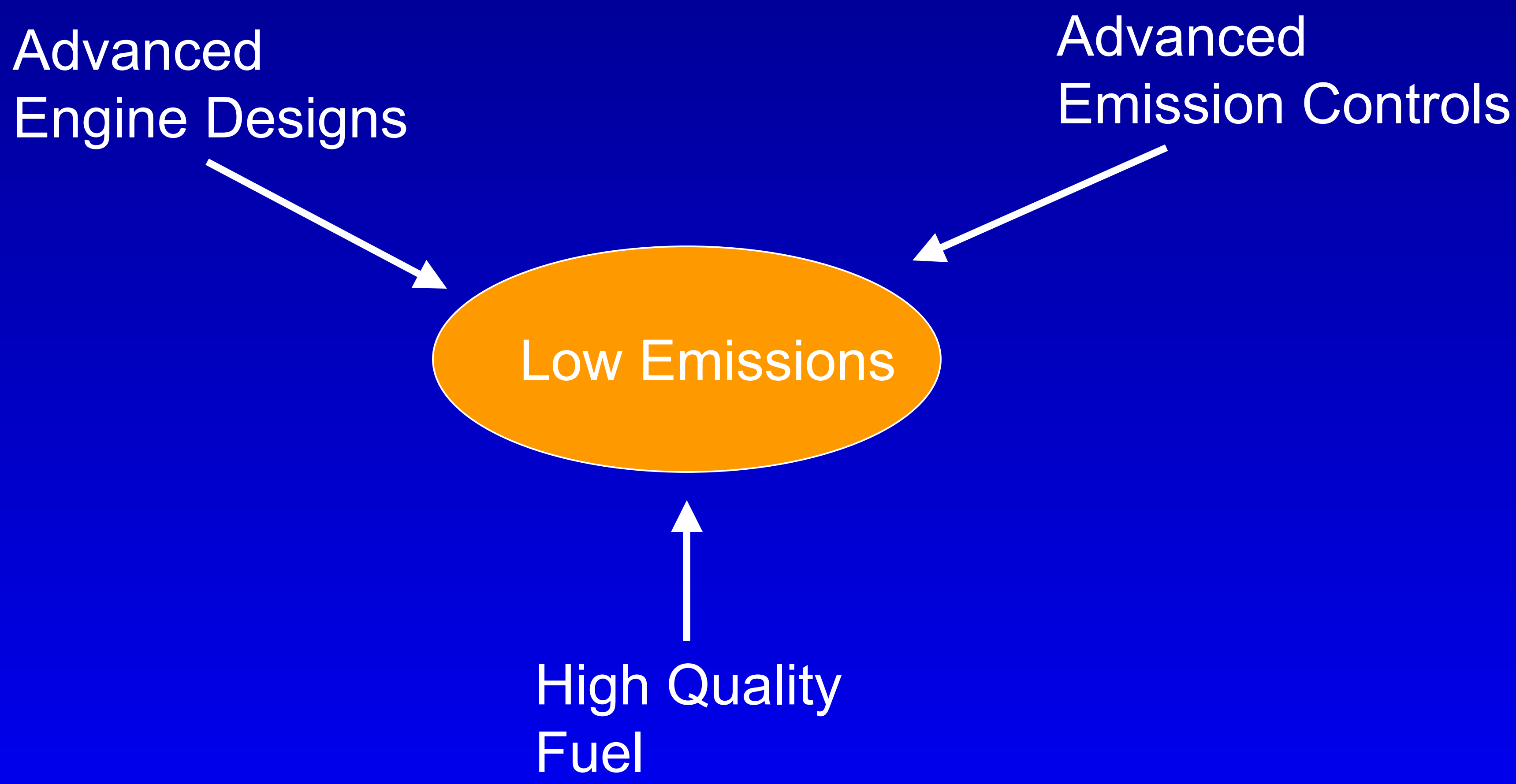
Presentation Outline

- An Introduction to the Manufacturers of Emission Controls Association (MECA)
- Background
- Review of Capital and R&D Investments Being Made
- Review of the Technical Progress Being Achieved
  - Diesel particulate filters
  - NOx adsorbers
- Conclusions

Introduction to MECA

- MECA Is an Association of Over 40 Companies that Are Developing and/or Manufacturing Emission Control Technologies for the Full Range of Mobile Source Vehicles and Equipment
- Member Companies Have Over 30 Years of Experience and a Proven Track Record in the Development and Manufacture of Advanced Emission Control Technologies

Background: Meaningful Emission Control Reduction Requires a Systems Approach



Background: The Contribution of Emission Control Technology in Meeting Clean Air Objectives

- Emission Control Technology Has Played a Key Role in the Success of the U.S. Mobile Source Emission Control Program
- Since the 1970s, Emission Control Technology Has Helped Meet and Achieve Emission Standards and at a Cost Typically Well Below the Original Estimates

Background: The Reasons Behind the U.S. Mobile Source Emission Control Program Technological Success Story

- Firm, Performance-Based Standards Established with the Lead Times Necessary to Develop the Needed Control Strategies
  - Provide the regulatory incentive and justification to make the capital and R&D investments necessary
  - Healthy competition in the marketplace
- Close Cooperative Development Efforts Between the Engine/Vehicle Manufacturers and the Emission Control Manufacturers
- The Petroleum Industry's Ability to Provide the Fuels Needed to Ensure the Effective Performance of the Engine/Emission Control System

Background: The Design Criteria for Technology Development

- Meet the Applicable Emission Standards and Durability Requirements with an Adequate Margin of Safety
- Minimize Adverse Impacts on Fuel Economy and, Where Possible, Enhance Fuel Economy
- No Adverse Impacts on Vehicle/Engine Performance and, Where Possible, Enhance Performance
- Meet Ultimate Users Needs
  - Minimize Costs to the Extent Possible
  - Emission Control System Reliability
  - Emission Control System Transparency

Investments to Develop and Commercialize Exhaust Emission Control Technology

- The Emission Control Industry Is Making the Investments Necessary to Ensure Needed Technology Will Be Available
- Results of Third-Party Survey of MECA Members on Investments Being Made to Develop, Optimize, and Commercialize the Technologies that Will Be Needed to Help Meet the 2007 HDE Standards (12 Companies Responding)

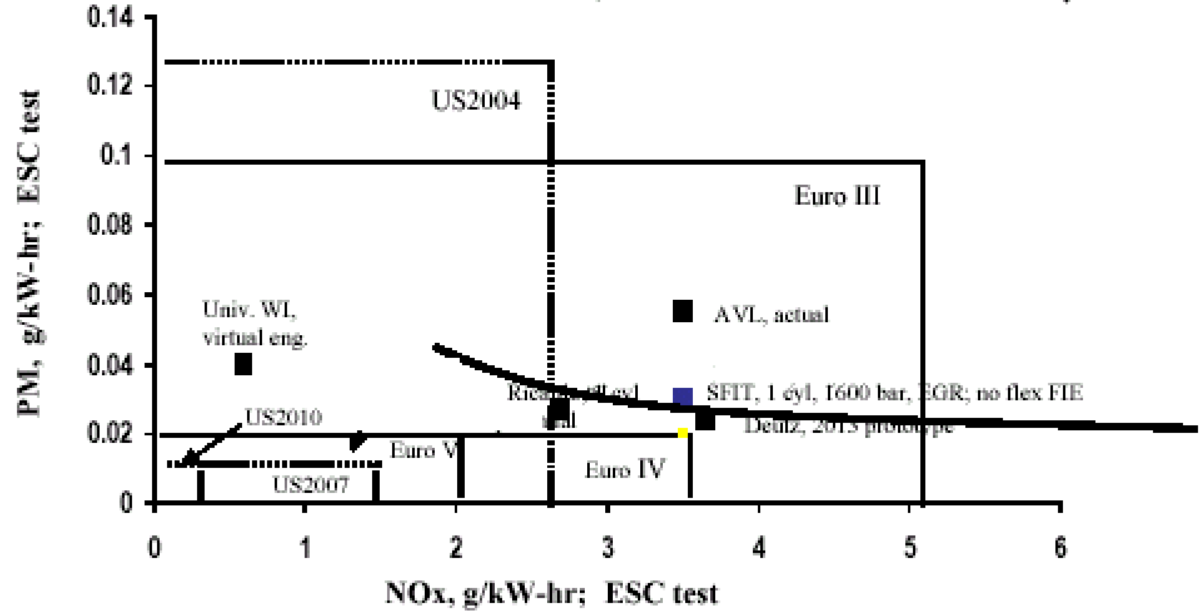
Total R&D Expenditures	$912,800,000
Total Capital Expenditures	$668,800,000
Total Expenditures	$1,581,600,000

Investments to Develop and Commercialize Exhaust Emission Control Technology

- Results of MECA Third-Party Survey (cont.)
  - Types of investments include:
    - New or expanded production facilities
    - New or expanded research and testing facilities
- Capital and R&D Investments Are Being Made Based on the Following:
  - Reliance that the 2007 HDE standards/low sulfur diesel fuel will be implemented as adopted
  - Confidence that the needed diesel exhaust emission control technologies will be developed and commercially available on time to help meet the applicable emission standards and durability requirements

Where Will HDD Engines Be in 3 to 7 Years?

To hit a NOx level of about 1.2 g/bhp-hr (1.6 g/kW-hr) in 2007, nominally 40 to 50% NOx efficiency is needed. To hit a 0.2 level, estimates are about 80 to 90% efficiency.



•Prototype Engines have cooled EGR, combustion optimization, fully flexible fuel injection, staged turbocharging, multi-hole injectors, high pressure injection.

Japan 2005 = Euro V in 2008

Developments in Diesel Particulate Filter Technology

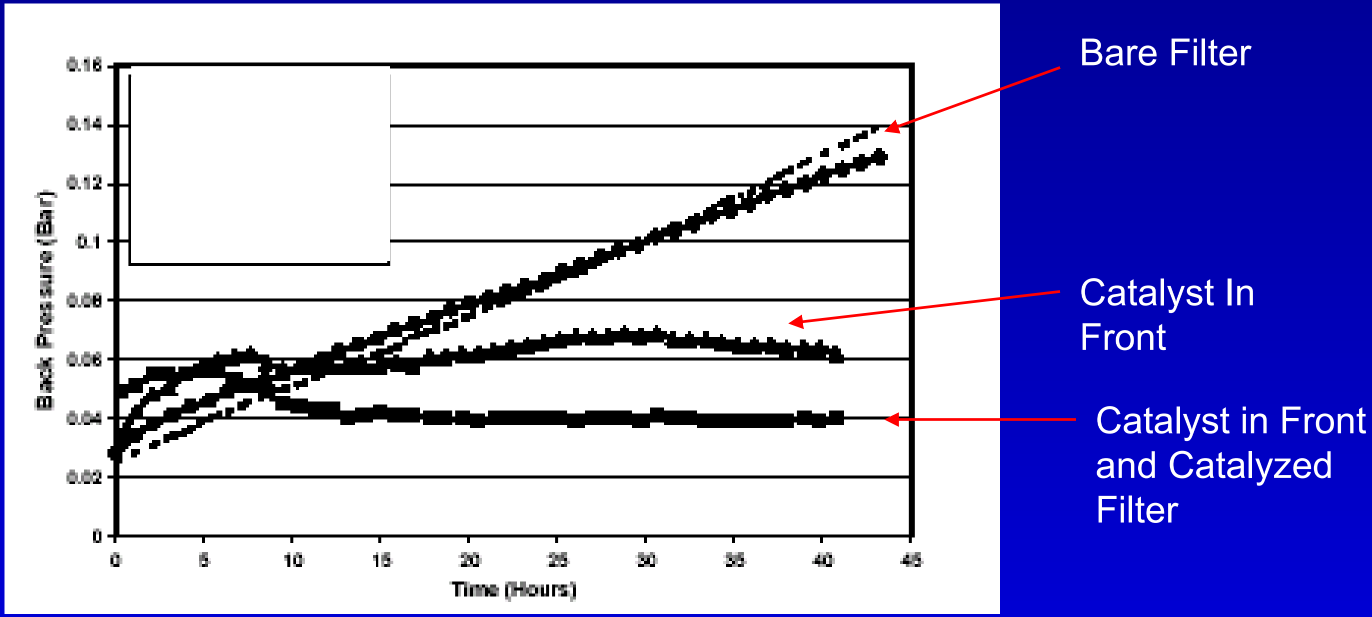
Advances in Diesel Particulate Filter Control Technology

- Improvements in Filter Regeneration
- Reducing Pressure Drop
- Ash Removal

Diesel Particulate Filters Are a Proven, Durable Technology that Nearly Eliminates PM and Improvements Continue

Improved Diesel Particulate Filter Regeneration

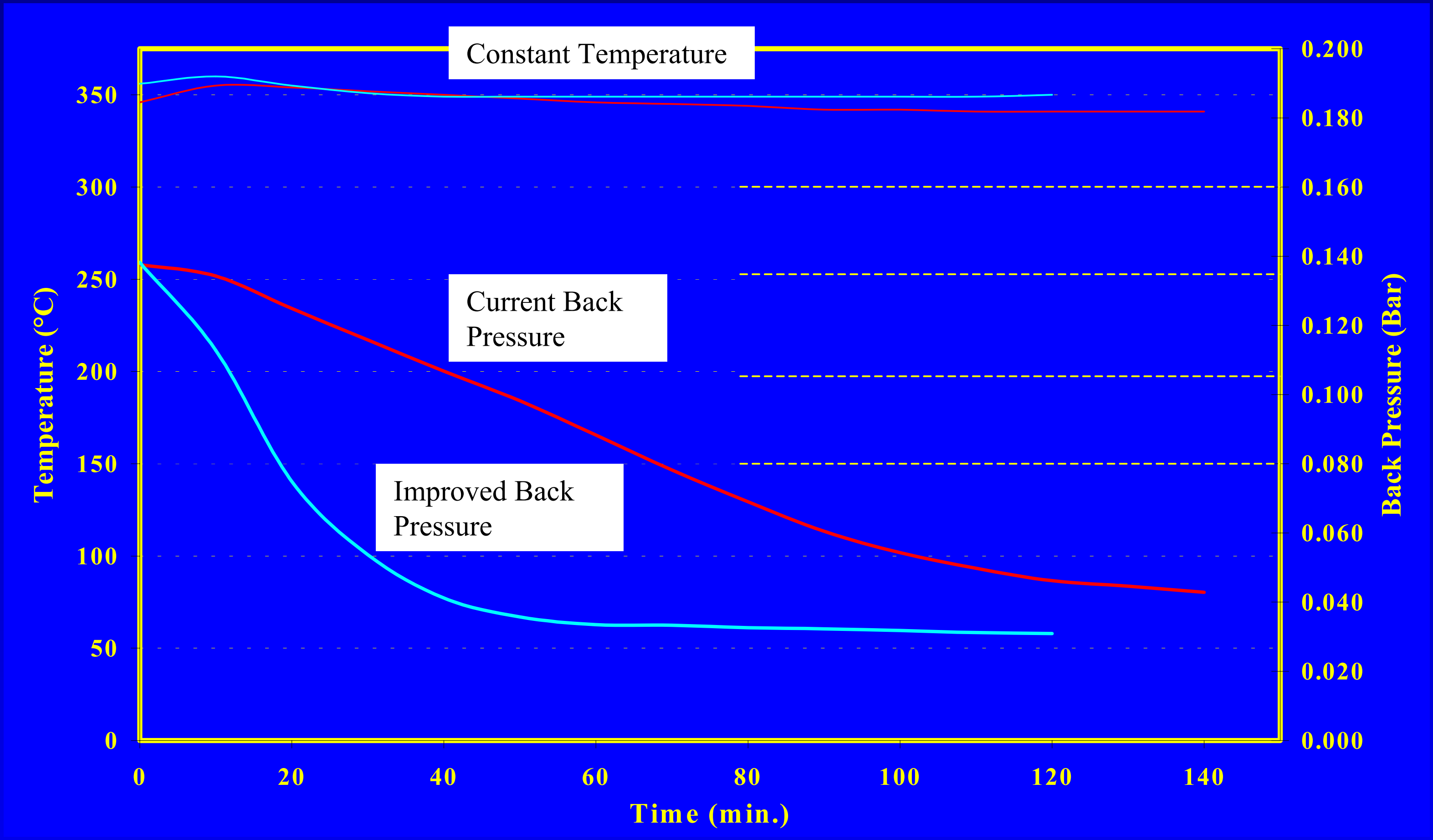
Using Both a Catalyst in Front of a Filter and a Catalyst on the Filter Improves Regeneration



New DPF system gives lowest back pressure in low temperature testing. LT cycle gives 160C<T<265C; mix of steady state and transient; 10 liter 210 kW turbo bus

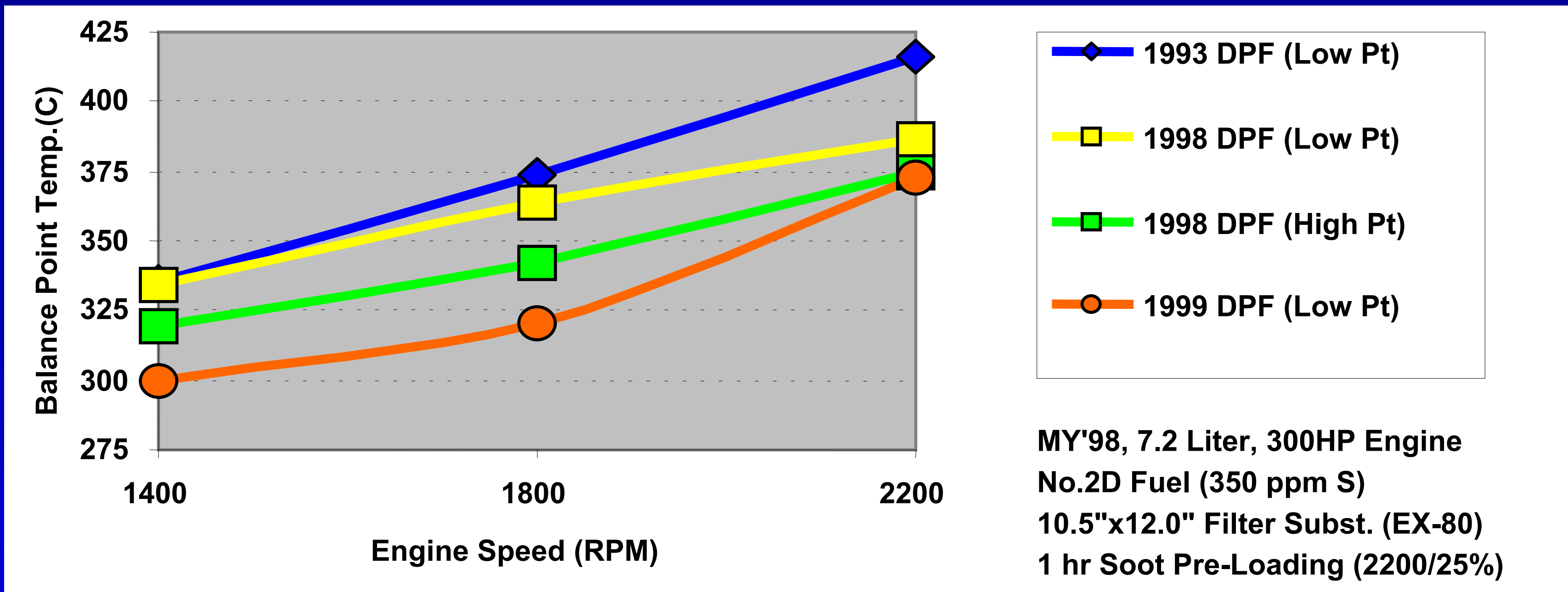
Source: SAE 2002-01-0428

Regeneration of Filter Systems at 350°C



Source: MECA Company

Relative PM Filter Regeneration Performance as Measured by Steady State Balance Point Temperature Determination Test on Engine-Dyno Stand

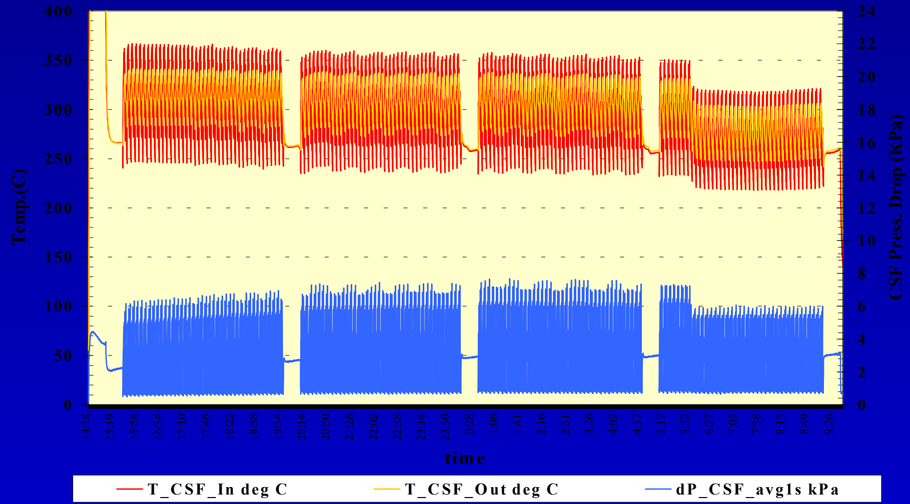


Continued development resulted in reduction in balance point temperatures showing improved soot combustion performance.

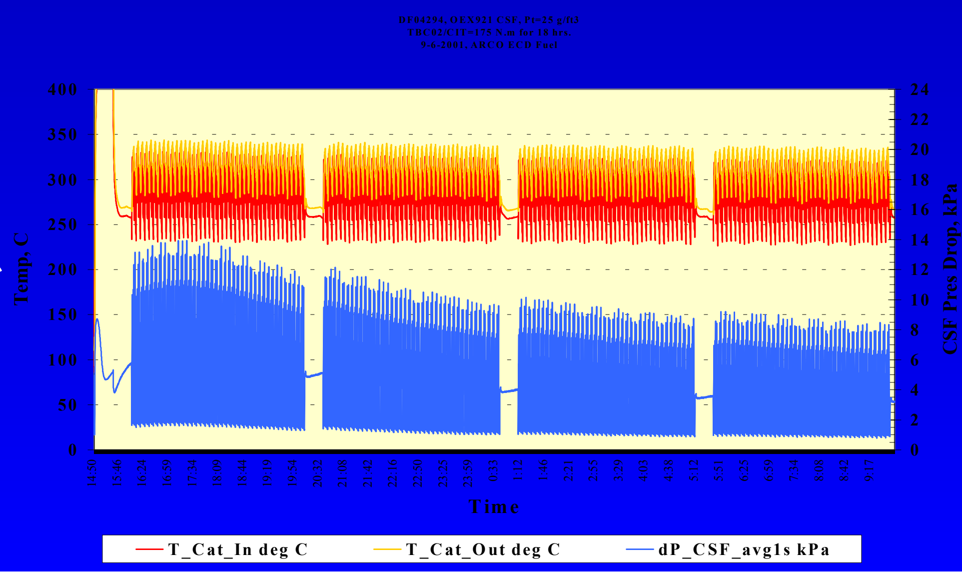
Source: MECA Company

Relative PM Filter Regeneration Performance as Measured over Simulated Transient Cycle Testing on Engine-Dyno Stand

1999 DPF, Med Pt



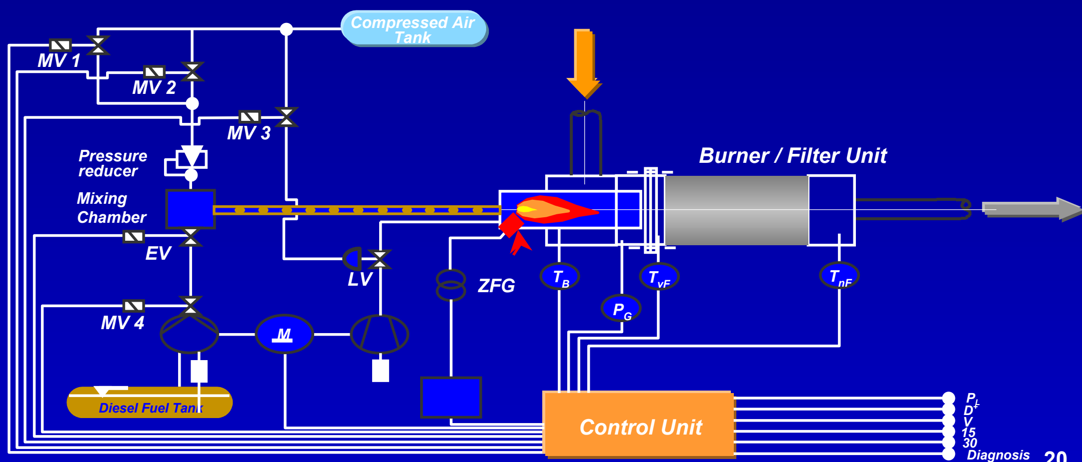
2001 DPF, Med Pt



- **MY 2000, 8.5 Liter, 275HP Engine**
- **Fuel: ARCO (< 15 ppm S)**
- **Simulated transient cycle with exhaust temperature range (230-360C)**
- **Note: Delta P response vs time:**
  - **1999 DPF increases then levels off**
  - **2001 DPF decreasing after short initial increase**
- **Improved PM burning performance with 2001 DPF**

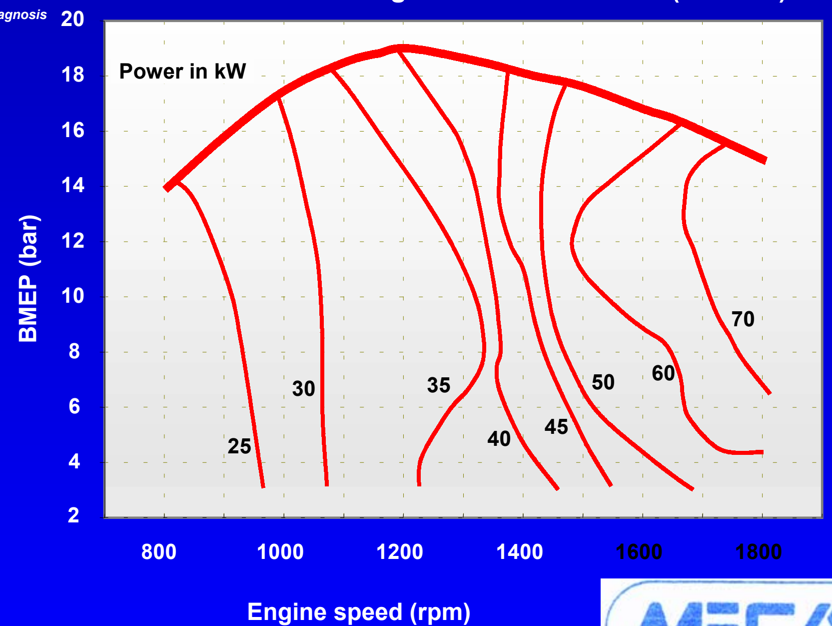
Source: MECA Company

Fuel Burning System Is Introduced to Aid Filter Regeneration



Complete burner system for retrofit applications. OEM applications might use an air pump instead of compressed air.

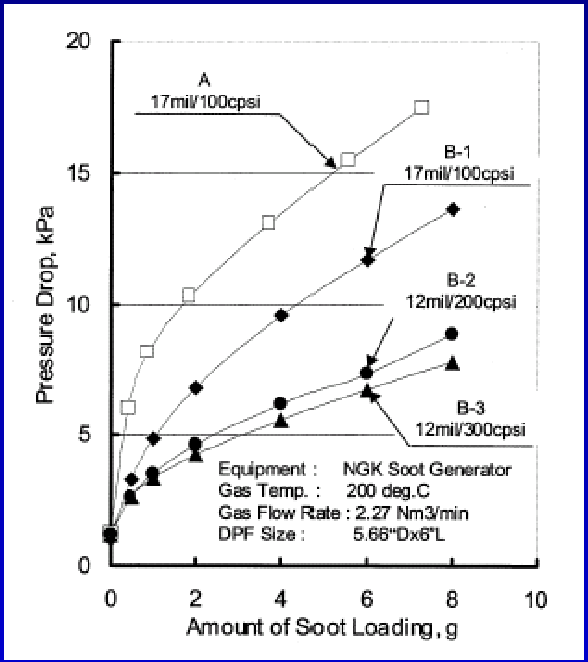
Power draw of the burner to heat exhaust to 650 degrees C depends on the load point. 2% fuel penalty is typical

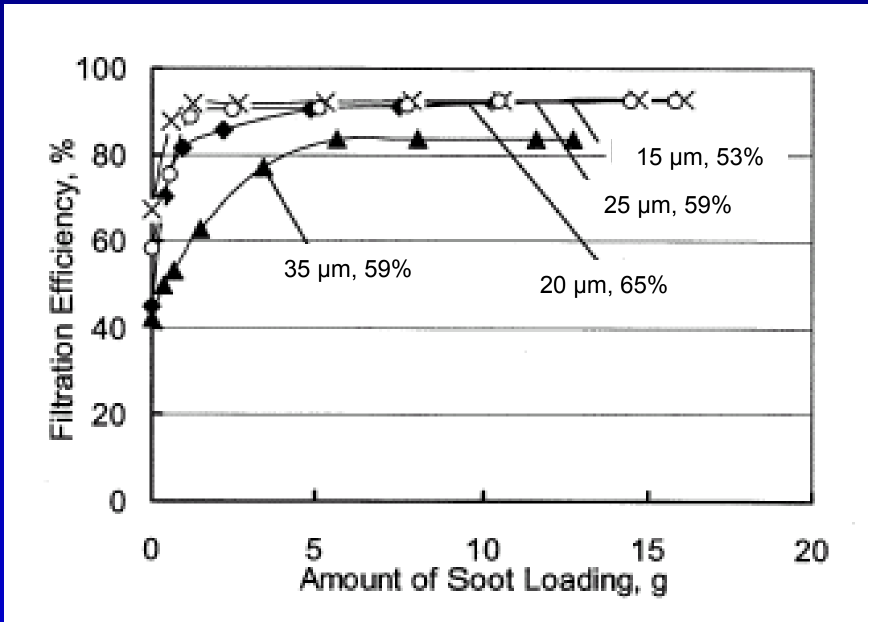


Source: Zeuna Staerker, AVL International Commercial Powertrain Conference, Budapest, 10/01

Reducing Pressure Drop

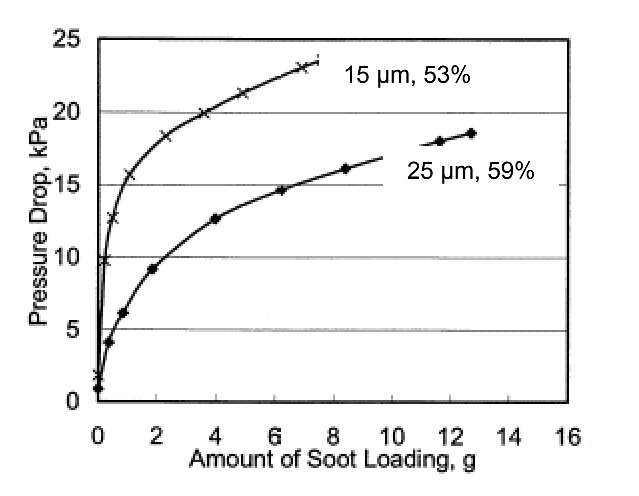
Cordierite Filters Are Improving as Pore Changes and Filter Geometry Are Being Understood





At higher cell densities, back pressure is strongly dependent on wall thickness. Porosity is 59% w/ 25 µm avg. (Type A is 53% and 15 µm)

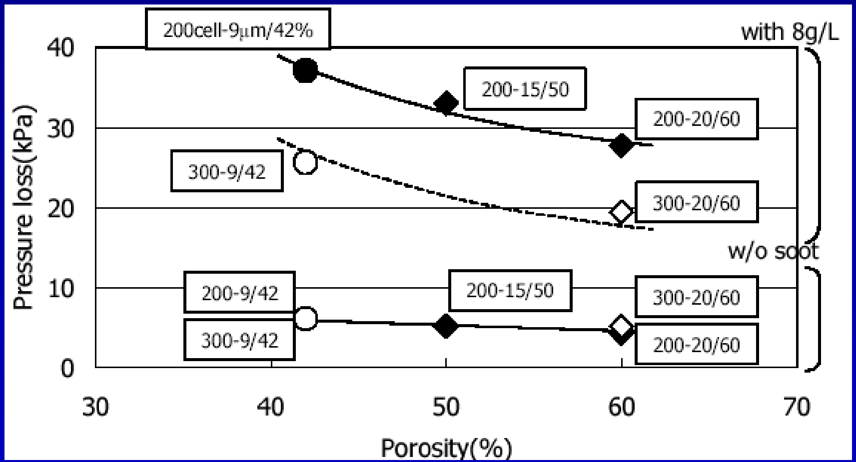
Filtration efficiency by mass is dependent on pore size if > 25-30 µm



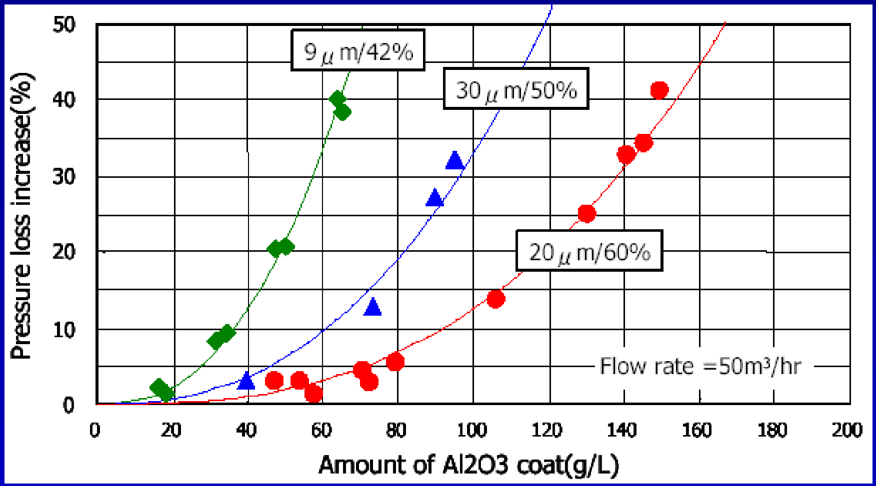
Pressure drop of washcoated filters can be dropped with pore engineering, 300/12, 100g/liter

Source: NGK 2002-01-0322

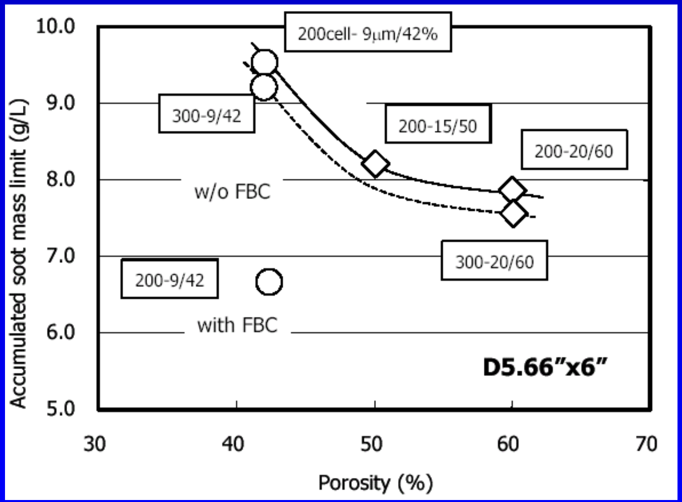
SiC Filters Are Being Optimized



Pressure drop dependency on cell geometry and porosity is different for loaded and unloaded SiC filters.



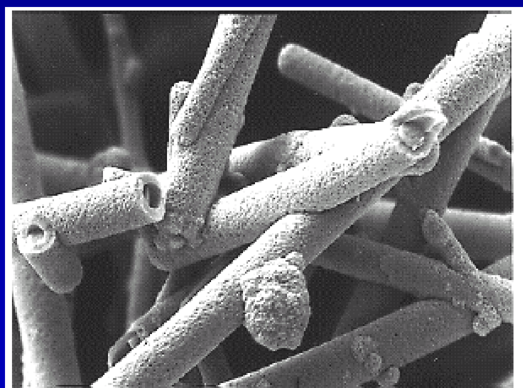
Pressure drop of washcoated filters is more dependent on percent porosity than average pore size. With large pores, WC is impregnated into filter, dropping effective pore size.



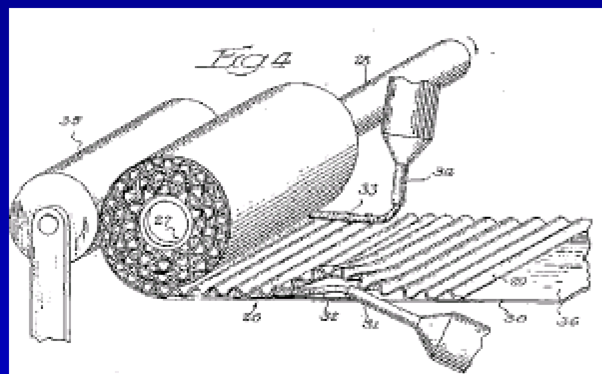
Filter durability limit is reduced as thermal mass is removed.

Source: Ibiden SAE 2002-01-0325

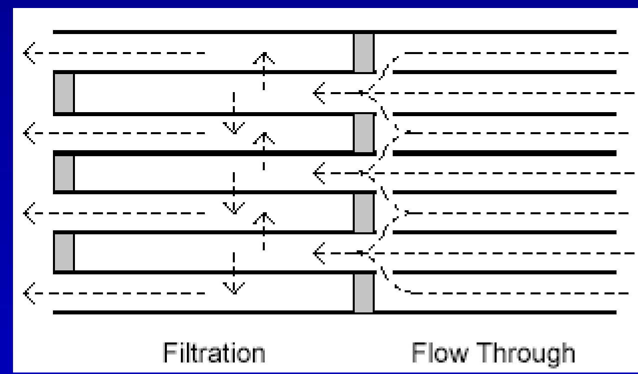
A New Fiber Filter



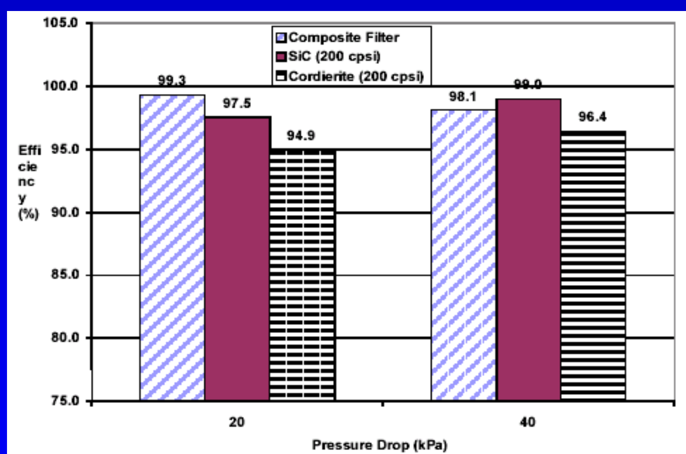
Alumina fibers are CVD coated with SiC. 3 μm diameter



Fibers are made into paper and rolled into a plugged honeycomb.



Various geometries can be attained. Here, a filter is combined with a flow-through catalyst in one unit.

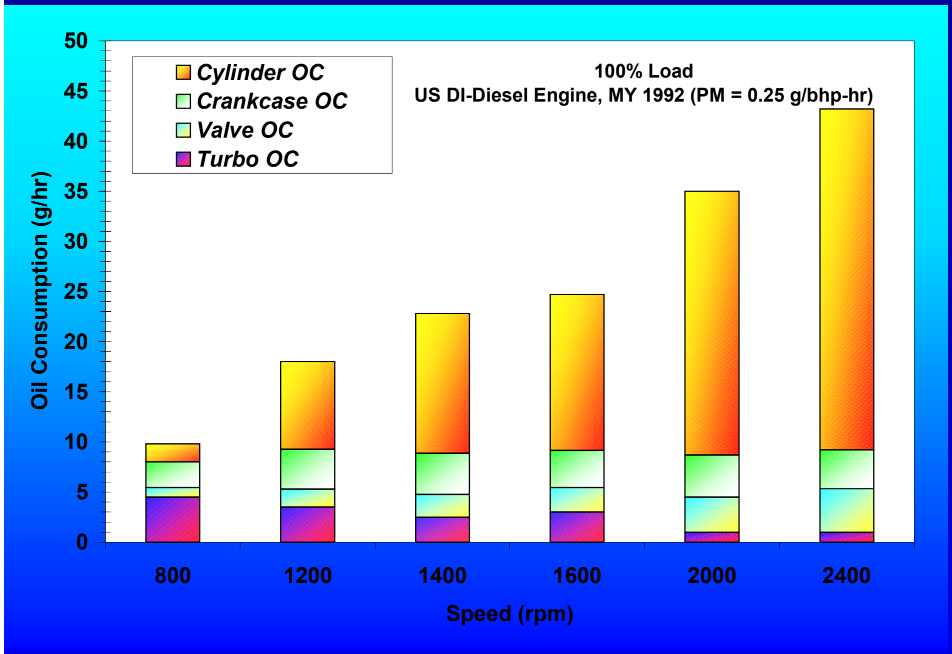


Source: SAE 2002-01-0323

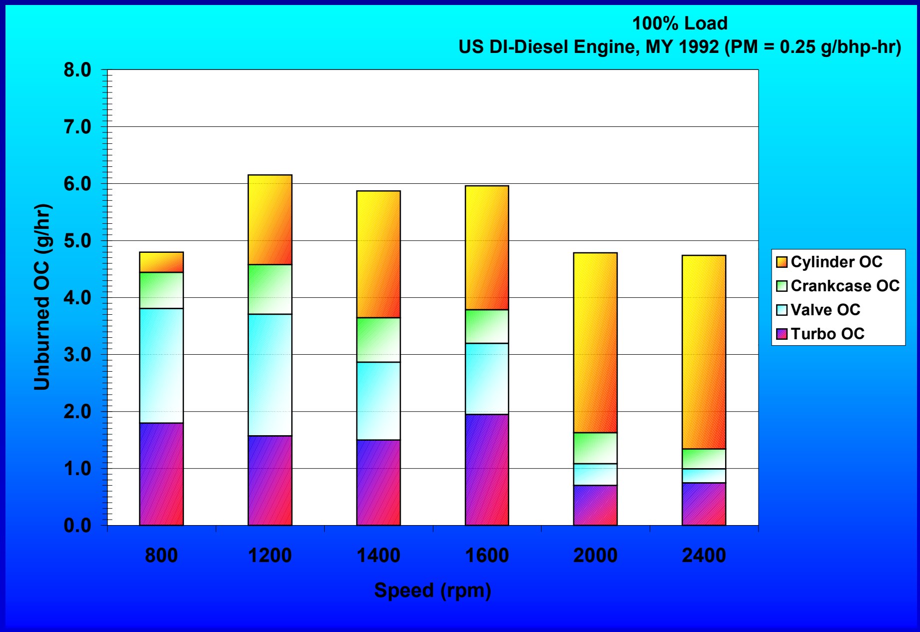
Improved Ash Handling

Sources of Oil Ash Are Being Investigated

Sources of Oil Consumption



Sources of Oil Emissions

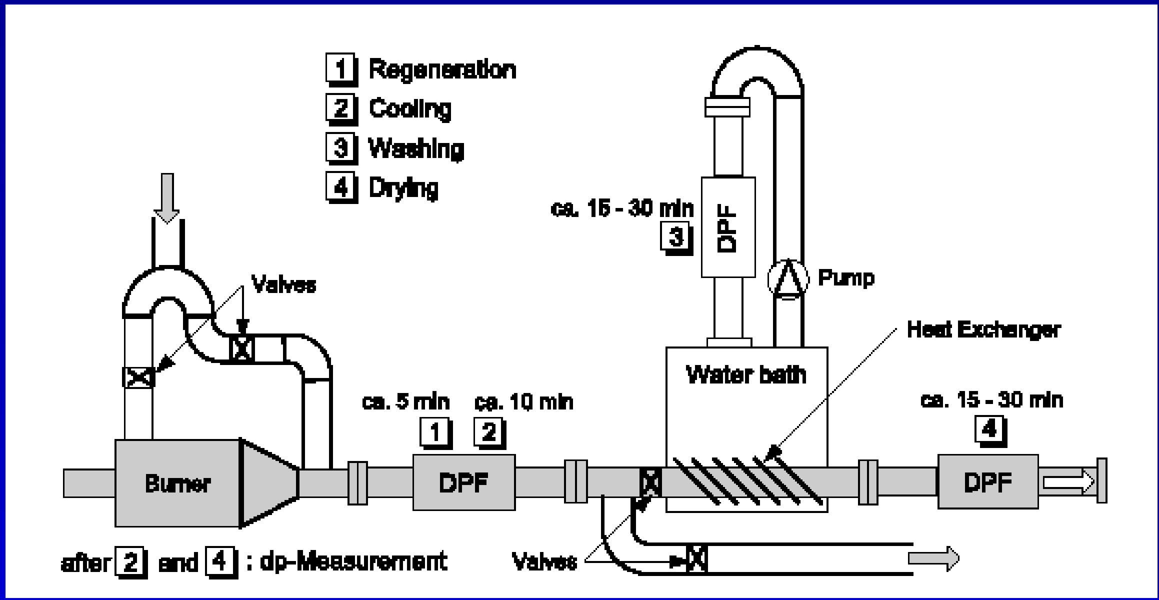


- ☞Low Speed: Highest Contribution from Turbo
- ☞High Speed: Highest Contribution from Cylinder

- ☞Low-Speed: Highest Fraction from Valve
- ☞Mid-Speed: Highest Fraction from Turbocharger
- ☞High-Speed: Highest Fraction from Cylinder

Source: SwRI - Weststart Conf. 2/02

Ash Cleaning from DPFs



SAE 2001-01-3199

Cleaning process:

1. Burn-off of soot with hot air
2. Cleaning with water and air under "high" pressure.

Source: Picture as per ADAC website, Aug. 28, 2001

All fuel delivery trucks in the ARCO (BP) ECD retrofit program went 150K miles before ash build-up became an issue. Some trucks went 250,000 miles.

Source: BP SAE 2002-01-0433

MECA

Other Diesel Filter Developments

- Continuous Improvements to Make the Filter System Even More Flexible and Robust
- Maximize Regeneration Capabilities
  - Engine management, filter design, and location
- Integrate NOx Adsorber and Diesel Particulate Filter Technologies to Benefit from Symbiotic Relationship

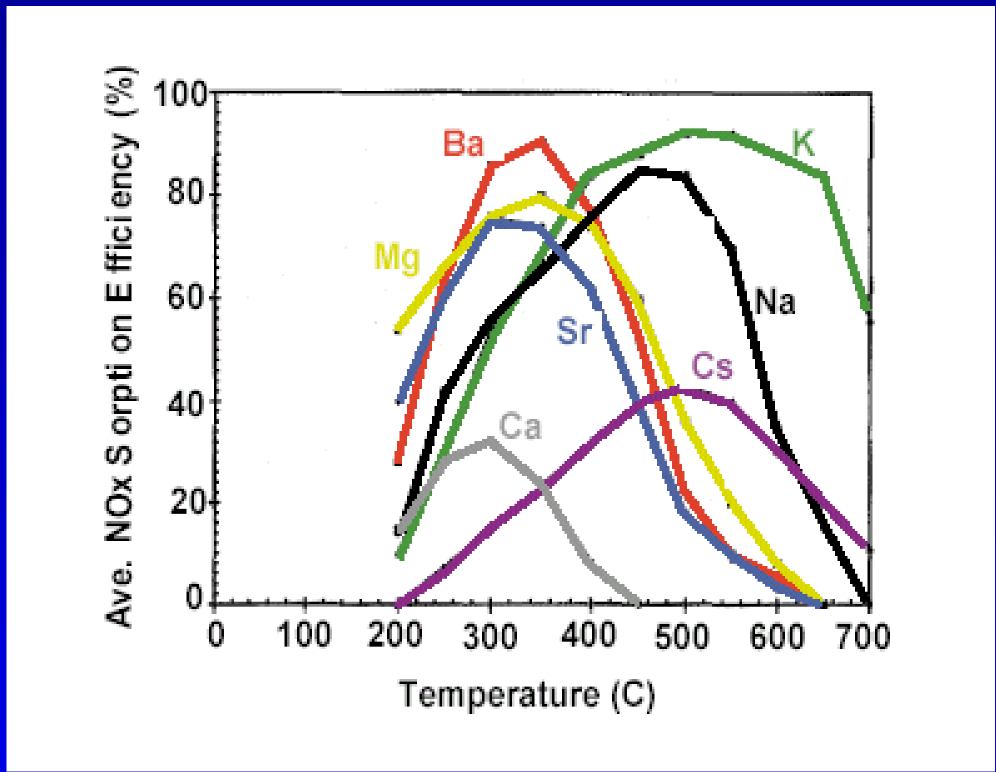
Recent Progress on the Development of NOx Adsorber Technology

Progress in Developing Emission Control Technology: NOx Adsorbers

- Areas Evaluated in EPA's Study
  - Improvements to broaden the temperature range over which the NOx adsorber is effective (temperature window)
  - Improvements in thermal durability (resistance to thermal sintering)
  - Improvements in methods and performance for desulfation (sulfur cleansing)
  - Improvement in systems integration (NOx regeneration, packaging, fuel economy)

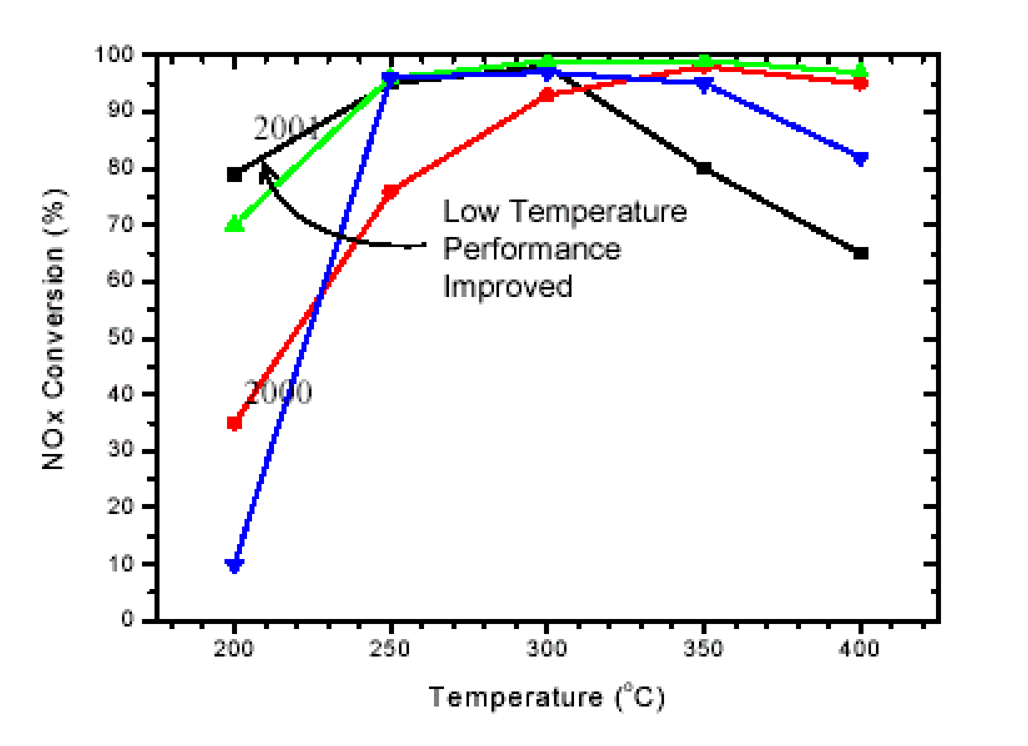
Operating Temperature Window, Control Efficiency, and Durability Improvements

A Variety of NOx Adsorber Compositions Can Be Used to Span the Range of Temperatures from 250 to 650+ Degrees C



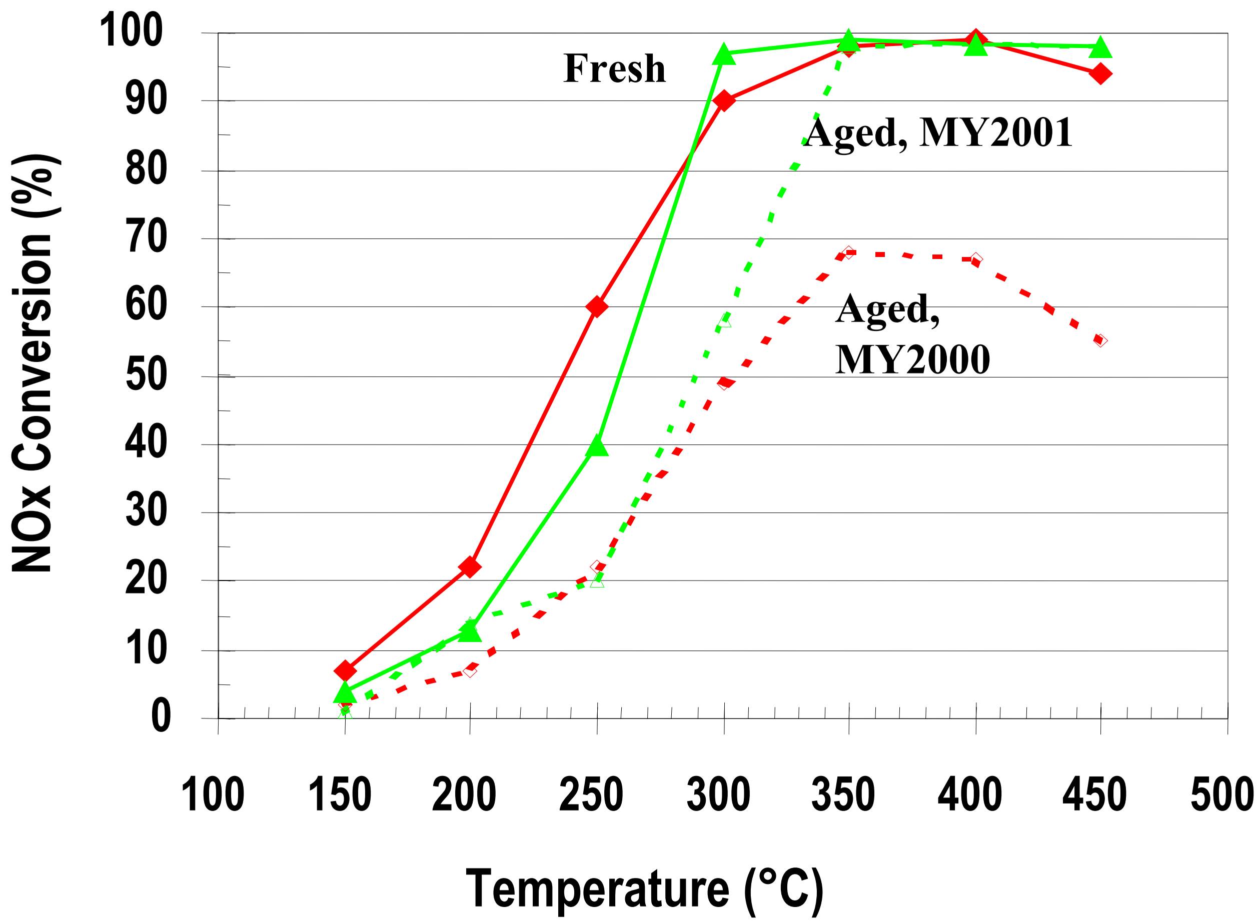
Source: Ford Motor Company

Continuous Improvements in Low Temperature Performance of NOx Adsorber Catalysts Are Realized while Maintaining HT Performance



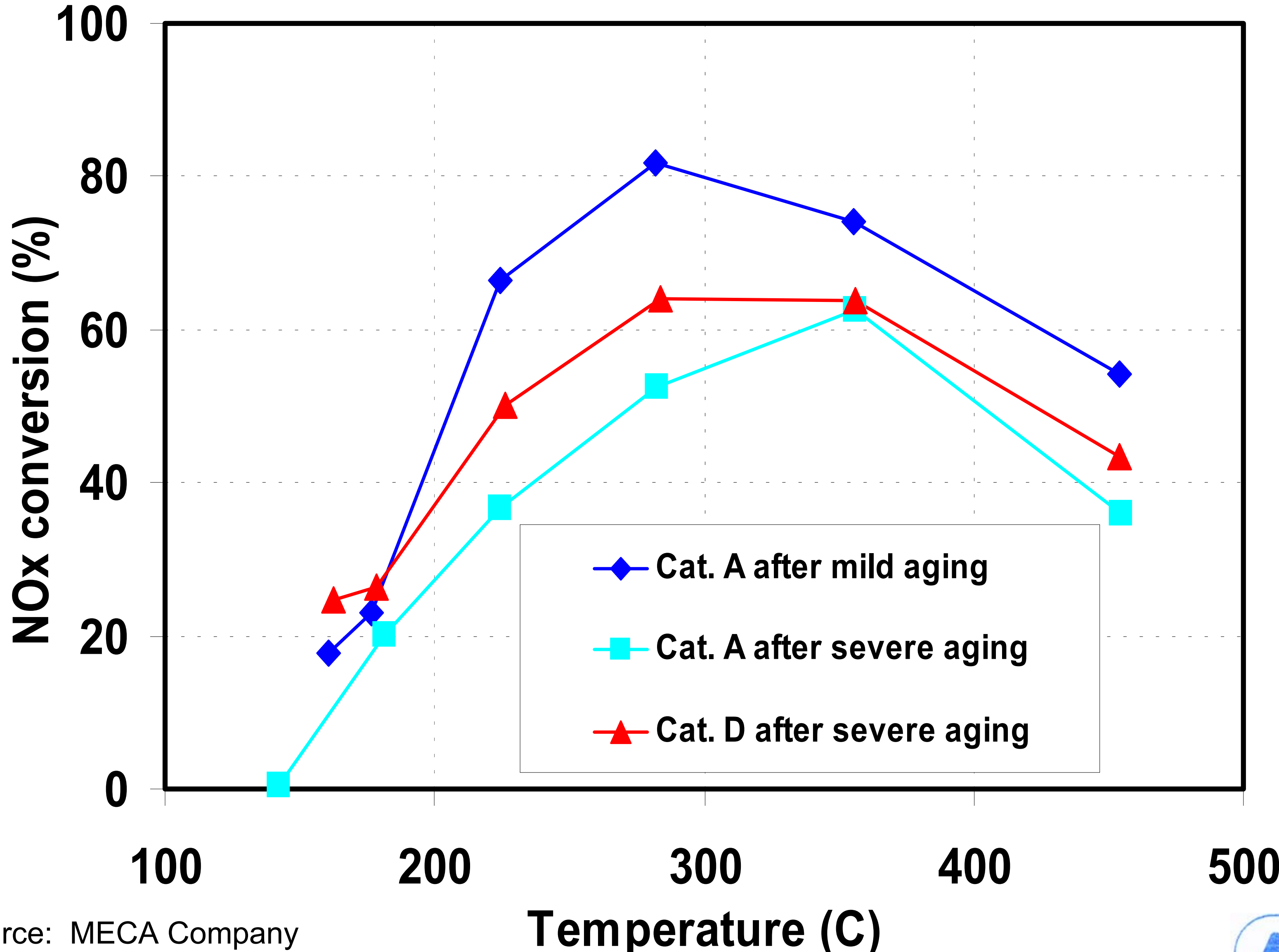
Source: MECA Company

NOx Adsorber Rich/Lean Durability Showing Improvement; Improved from 70% to 95+% Efficiency after Aging



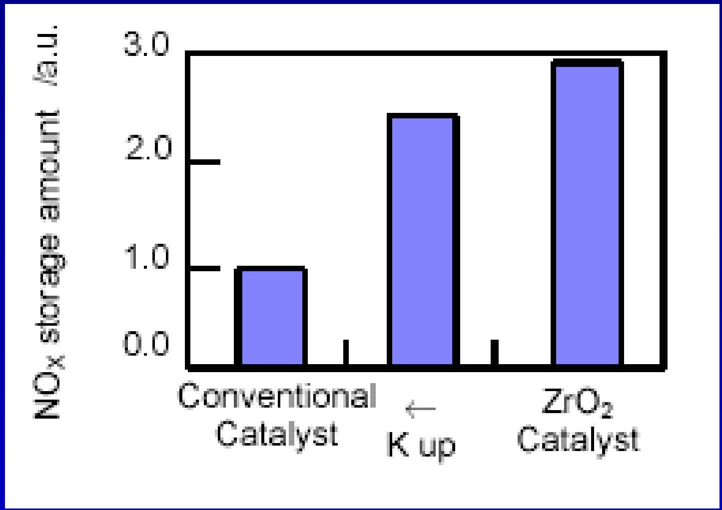
Source: MECA Company

Durability Improvement



Source: MECA Company

Improvements Are Continuously Being Made to NOx Storage Capacity



Newly developed NOx trap w/ ZrO_2 has higher capacity than plain K_2O. 500C

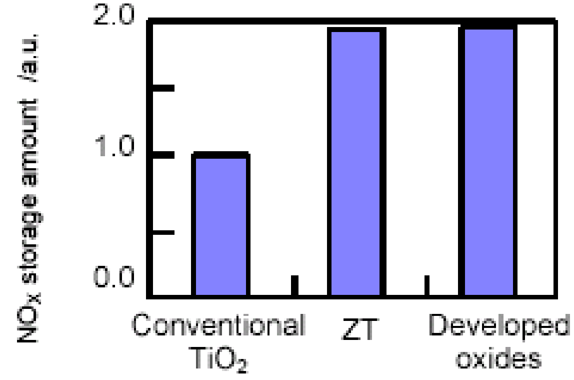
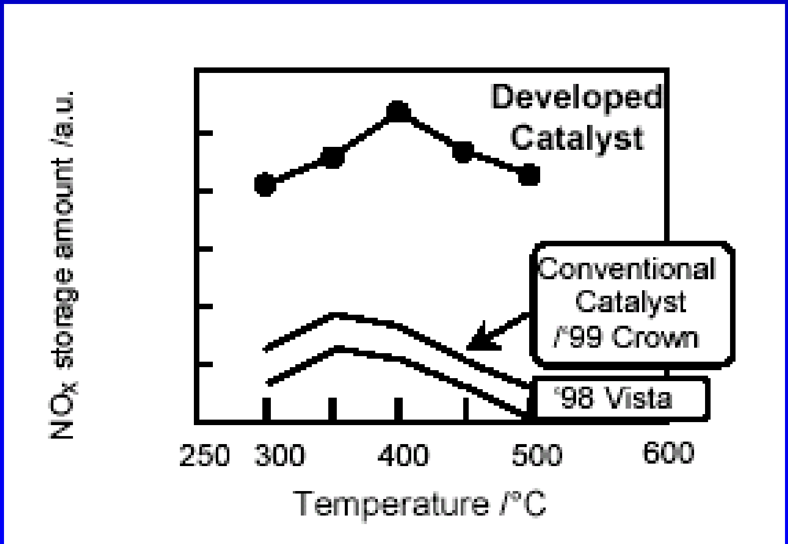


Fig.11 Relative NO_x storage amount after durability test.

Sample: Pellet catalyst (K/Pt/support)
Aging condition: A/F=22(55 s) ↔ A/F=12(5 s), 800 °C,4 h
Evaluation temperature: 500 °C (inlet gas temp.)



Source: Toyota SAE 2002-01-0732

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Increased Cell Density and Substrate Length Aid in Efficiency of NOx Adsorber

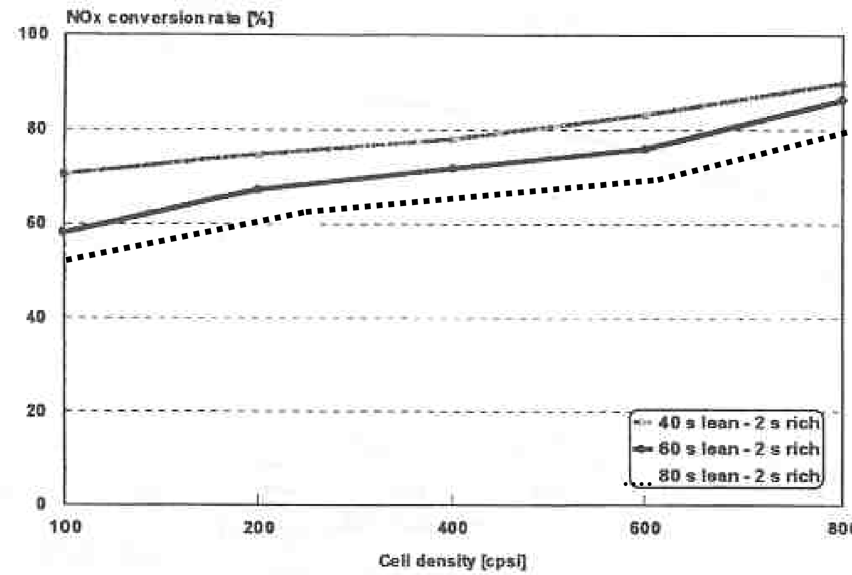

Fig. 7: NO_x conversion dependent on cell density

Catalyst dimensions: Ø 17 × 24 mm
Test conditions:
Gas inlet temperature = 300 °C
Space velocity (lean and rich) = 45000 h^{-1}
NO concentration in front of catalyst = 750 vppm

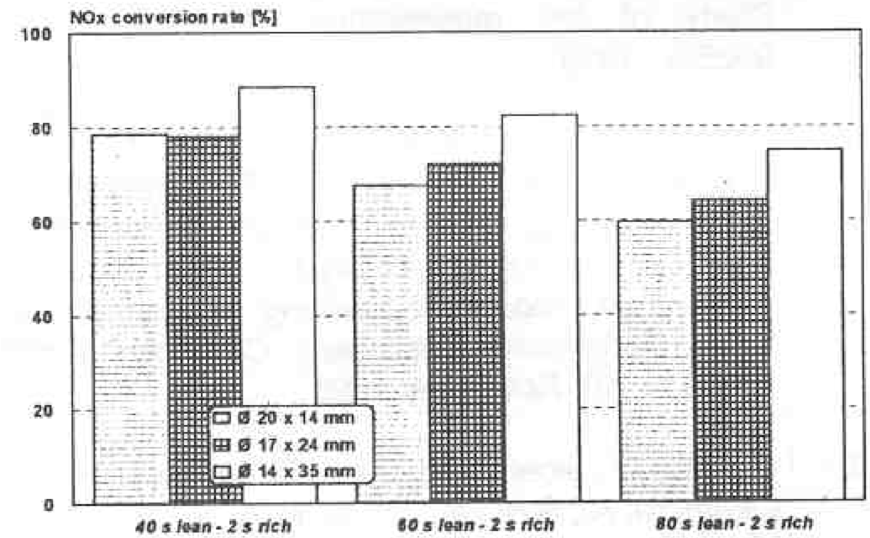

Fig. 9: NO_x conversion dependent on catalyst design

Catalyst dimensions: 400 cpsi
Test conditions:
Gas inlet temperature = 300 °C
Space velocity (lean and rich) = 45000 h^{-1}
NO concentration in front of catalyst = 750 vppm

The greater GSA of high cell density substrates helps NOx efficiency. 800 csi requires half as much rich period to regenerate as the 400 csi, and cuts emissions by 50%.

For fixed volume and space velocity, longer substrates regenerate easier and have higher efficiency.

Source: Emitec SAE 2000-01-0504

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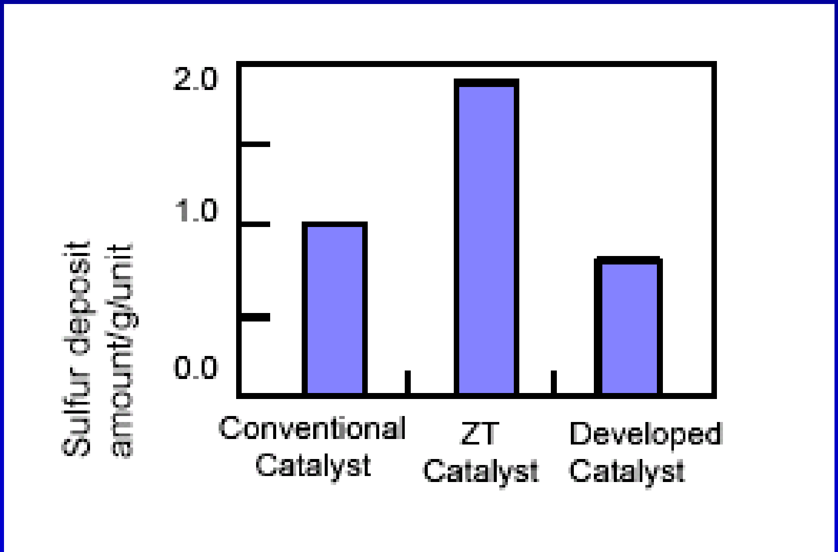
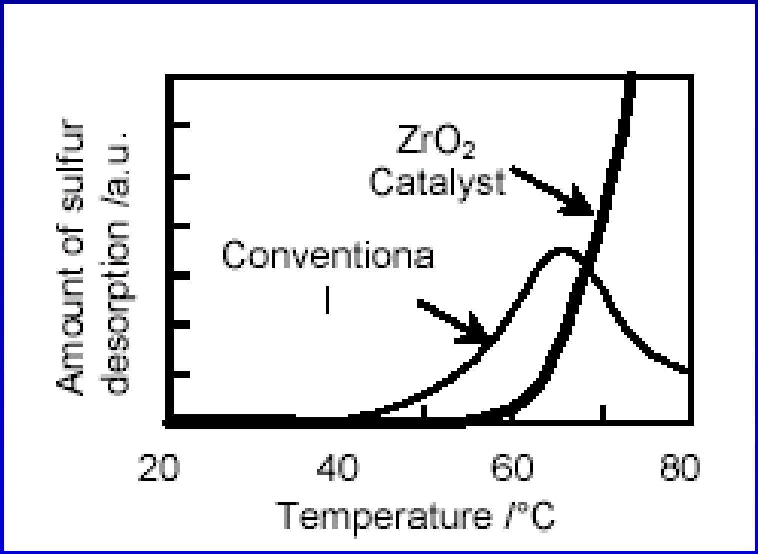
Improvements in Desulfation and Other Strategies to Address the Sulfur Issue

New NOx Adsorber Formulations Result in Higher Sulfur Resistance and Faster Sulfur Release

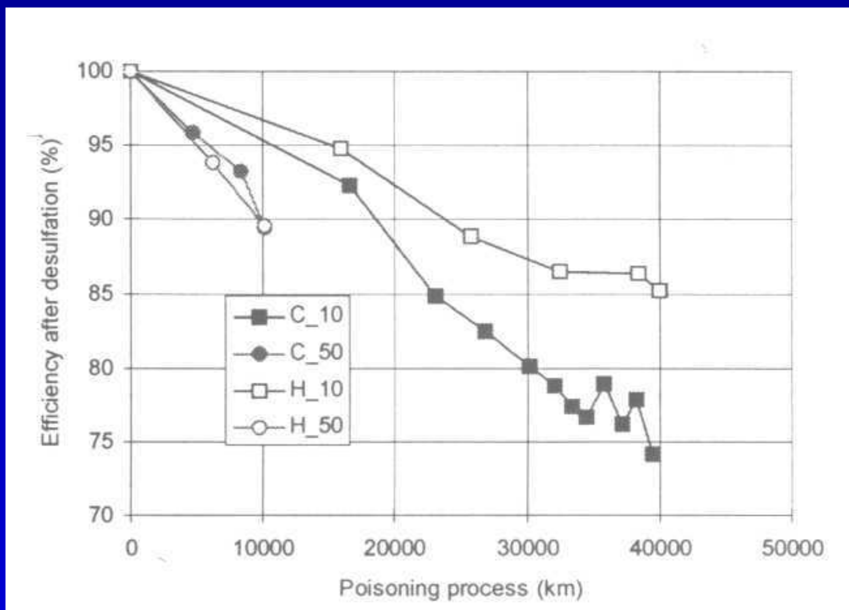




New catalyst desorbs sulfur faster.
Test condition: A/F=12, 200-800 °C, in rich gas (A/F=12) analyzed by SOX-analyzer
Rate of increasing temperature: 20 min/ °C

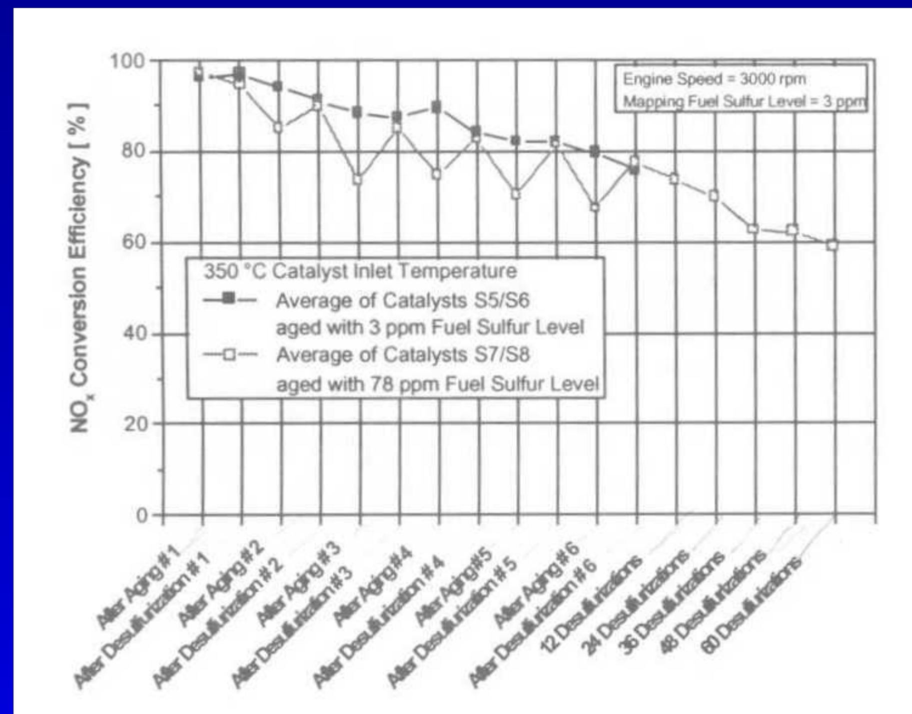
Source: Toyota SAE 2002-01-0732

Repeated Desulfations Cause Deterioration in Earlier NOx Adsorbers but with Signs of Flattening



Hexagonal cell NOx adsorbers stabilize at higher NOx efficiency levels and require fewer desulfations than square cell NOx adsorbers; 682C, A/F=13.2, 12 min.

Source: IFP SAE 2001-01-1934

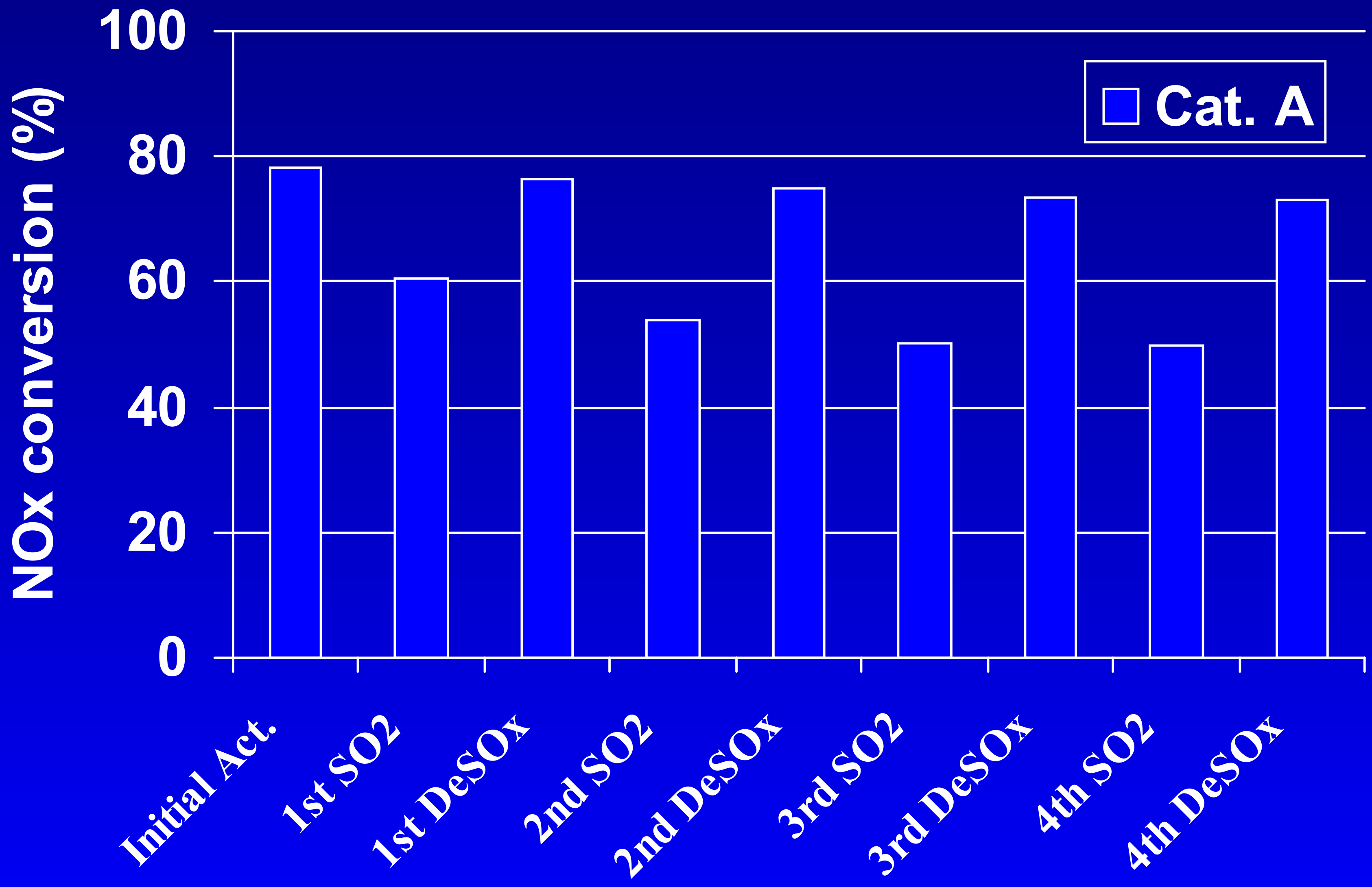


Desulf for 6 min every 10 hrs at 700°C

Source: DECSE SAE 2001-01-0510

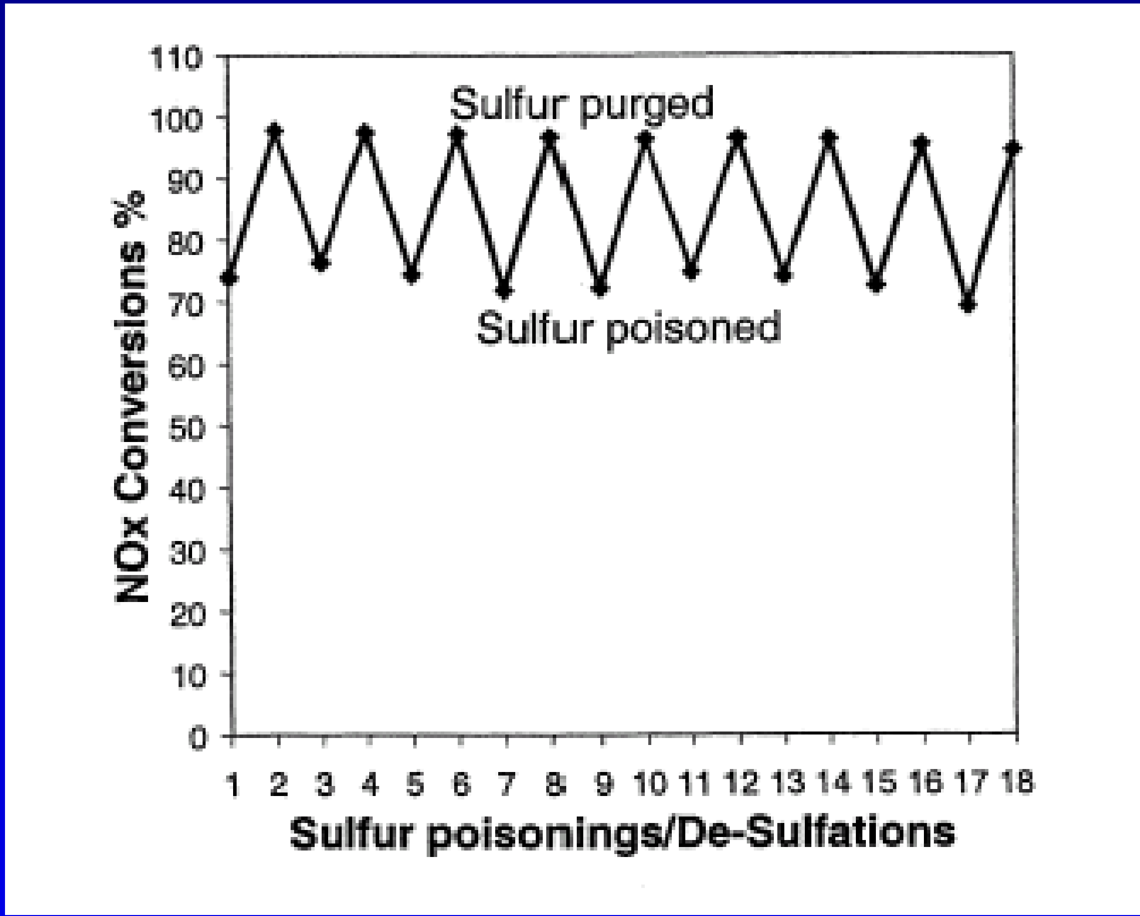
Desulfation fuel penalties of 0.5 to 1.0%

Newer Designs Have Improved Durability: NOx Adsorber Activity Recovered after Desulfation



Source: MECA Company

New Composite NOx Adsorber Materials Improve Performance

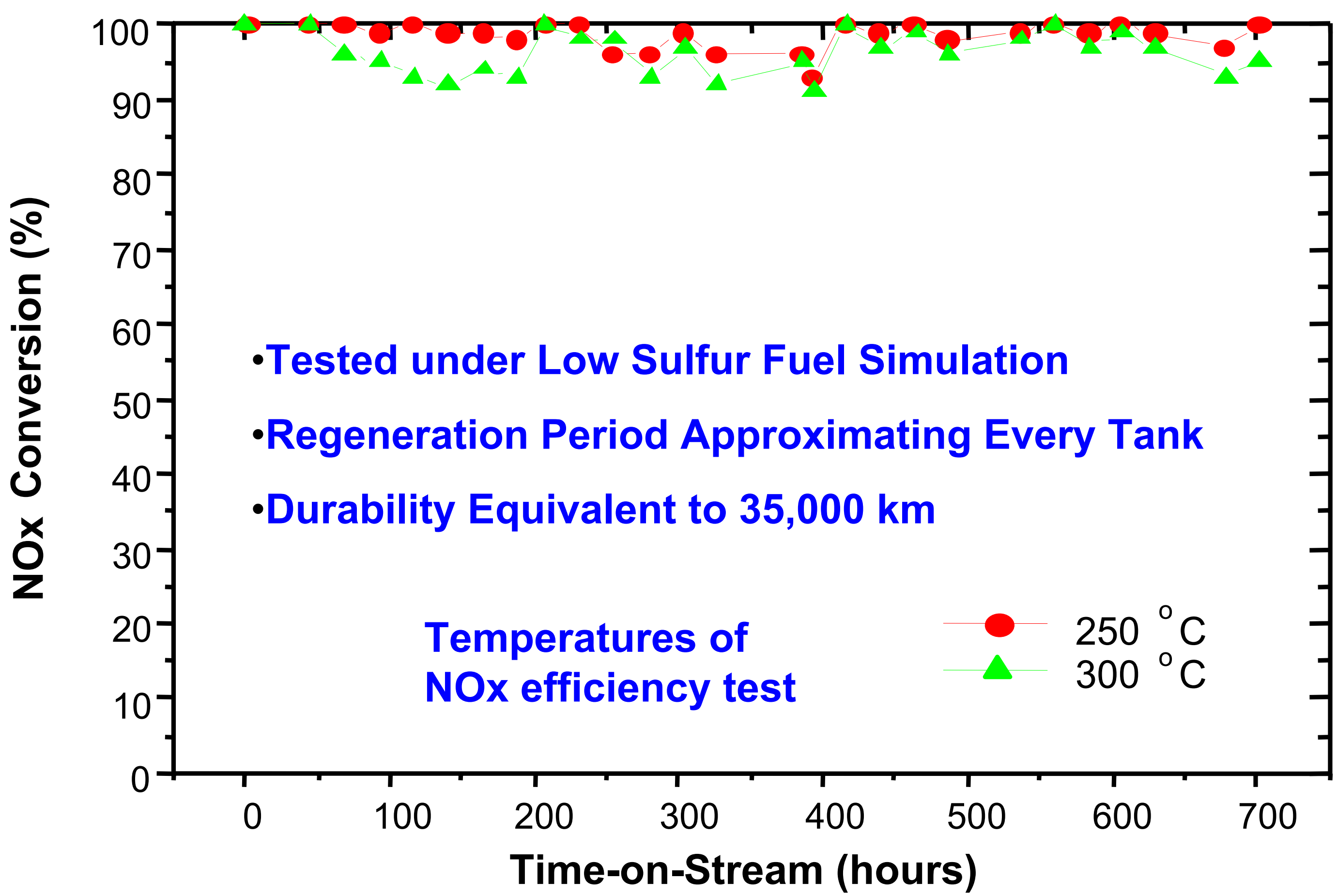


Sulfur tolerance of Ba-alkali NOx adsorber materials is improved. Ba materials oscillated between 30 and 70%. Tests at 350C. Sulfations at 700C for 10 min at A/F=13

Source: Delphi SAE 2002-01-0734

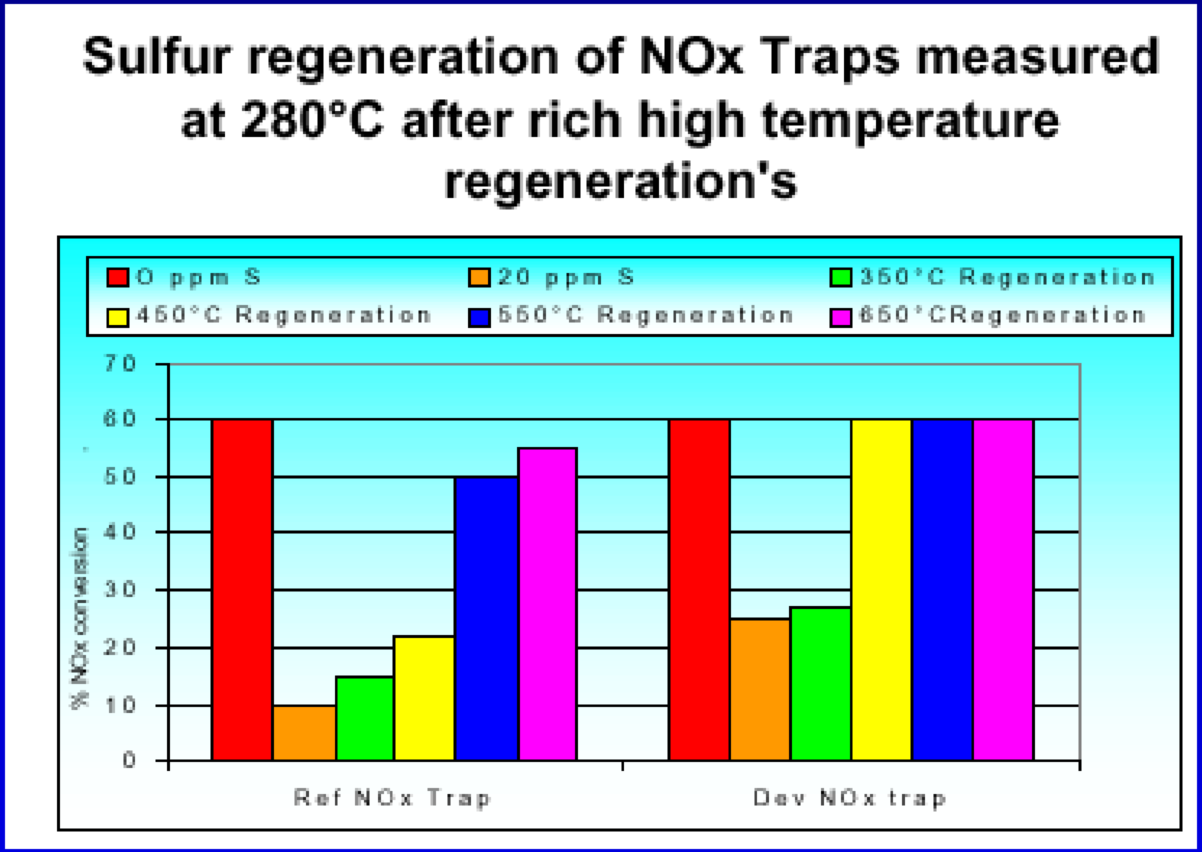
MECA

Catalyst Stable for 700 Hours in Simulated Engine Exhaust with 2 ppm SO_2



Source: MECA Company

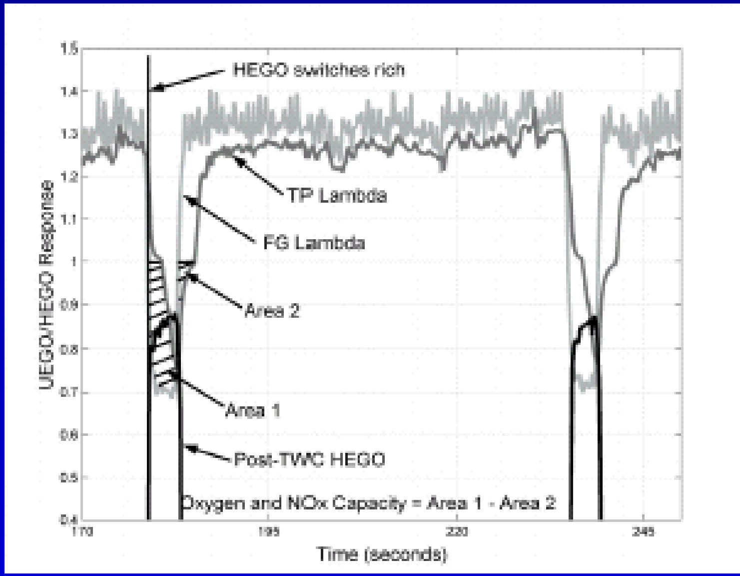
NOx Adsorbers Are in Development that Will Desulfate at as Low as 450 Degrees C



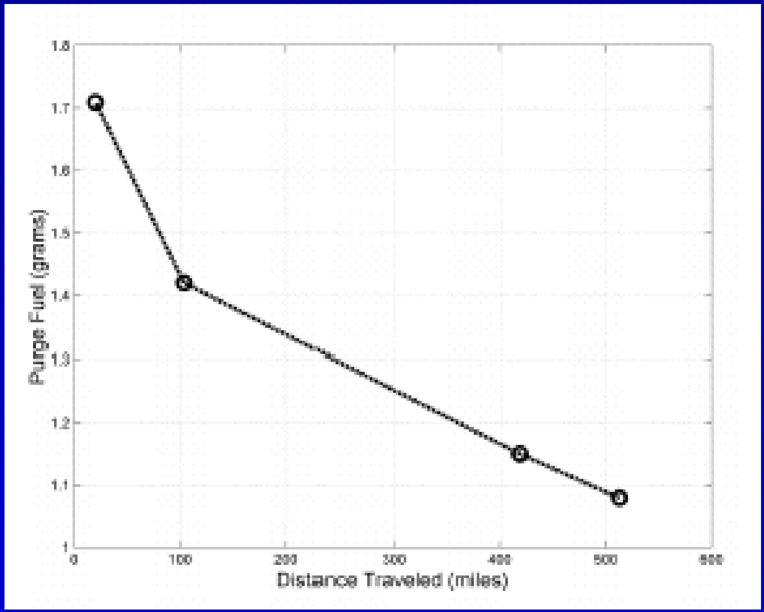
The development NOx adsorber returns to original performance after desulfating at 450 degrees C

Source: JMI, AVECC 2001 conf.

Methods of Diagnosing Sulfurization State of NOx Adsorbers Are Being Developed



The oxygen sensor responses to rich are used to infer state of the NOx adsorber

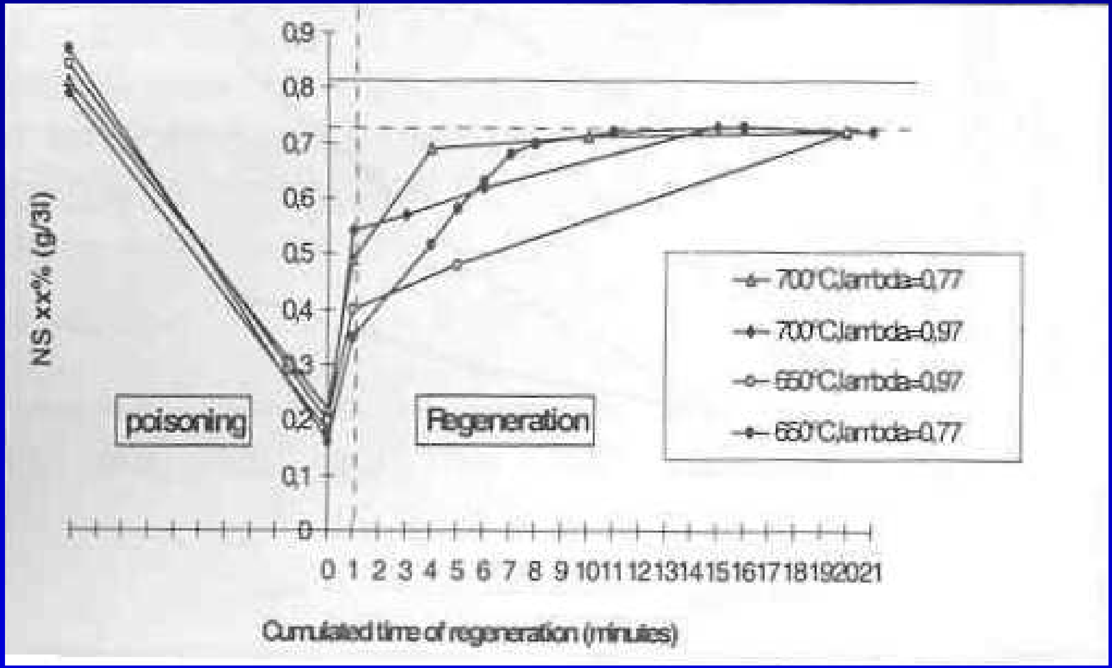


The amount of fuel to regenerate the NOx adsorber is the key indicator

Source: Ford SAE 2002-01-0731

MECA

Desulfation Is Best Accomplished Using a Staged Temp/λ Profile; Under Some Conditions "Natural Desulfation" Can Occur



Aged adsorber NOx capacity as a function of sulfur regeneration time and conditions.

1) In early desulfation, high temperature drives recovery

2) In later stage, λ drives recovery

3) Full recovery not obtained in any condition.

Source: Renault SAE 2000-01-1874

A/F Modulation Is Used to Desulfate NOx Adsorbers by Sending Lean and Rich Gases to the Adsorber to Generate an Exotherm

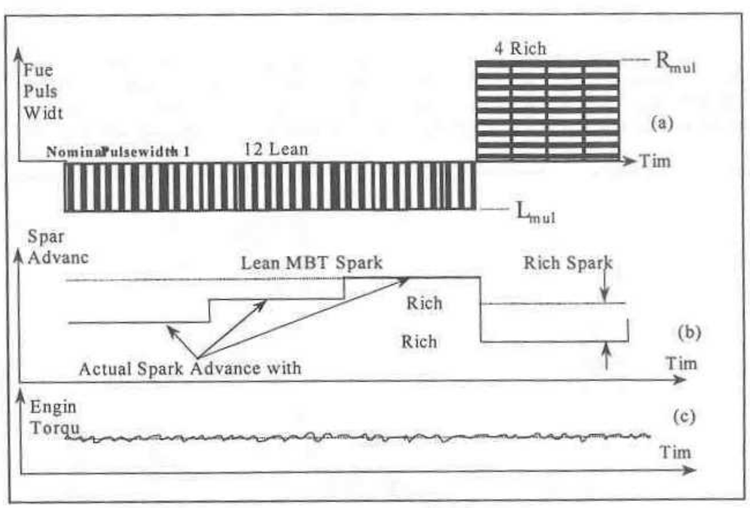


Fig. 7. Diagram illustrating the coordination of fuel pulse width injection and spark advance. 12 lean injections are followed by 4 rich injections. The spark advance is stepped from being retarded for lean A/F to MBT lean during the 12 lean injections. The spark is operated at retarded timing during the rich injections, resulting in a nearly constant engine torque during the fuel injection modulation.

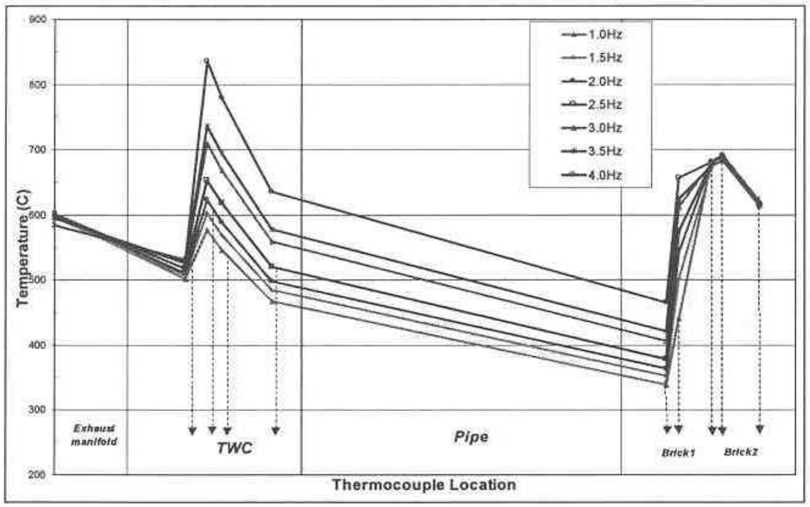


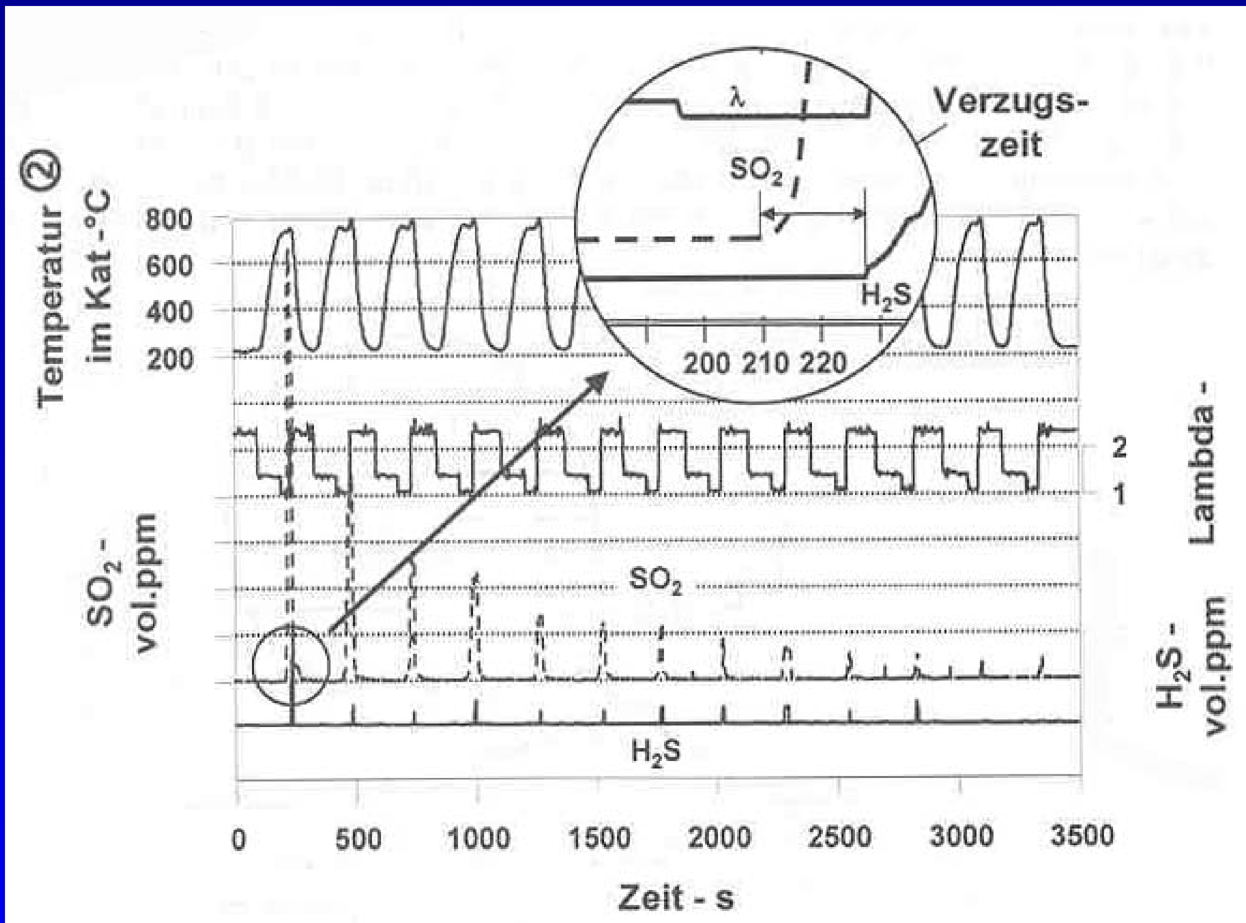
Fig. 9. Temperature profile of exhaust system during desulfation as a function of modulation frequency. The vertical arrows refer to the locations of the nine thermocouples, which are labeled 1 to 9 starting at the leftmost position in the TWC.

A/F and ignition timing plan. When desulfation is needed, 12 lean A/F injections (3 per cylinder) are followed by 4 rich injections. These are large enough to pass through the TWC to the NOx adsorber. Retarded ignition prevents torque upsets when going rich.

Although the TWC heats up significantly at 4 Hz modulations, the temperature profile in the NOx adsorber is flatter. 4 HZ is the preferred frequency.

Source: Ford SAE 2000-01-1200

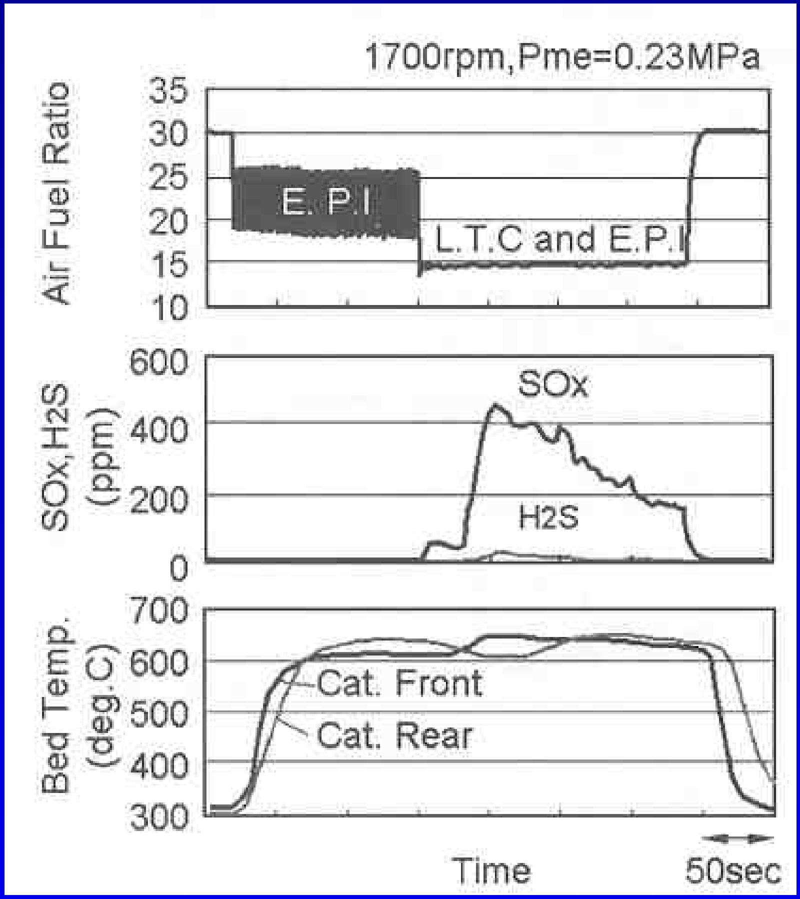
A Cycled NOx Adsorber Desulfation Strategy Prevents H_2S Formation



NOx adsorber desulfation is also cumulative (keep track of hot rich time)

Source: OMG& AVL Vienna Motor Symposium 4/01

A Combination of Auxiliary Fuel Injection and Combustion Control Is Used to Desulfate a NOx Adsorber without Releasing H_2S



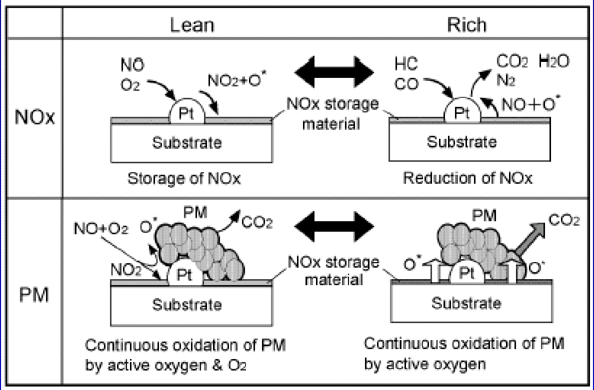
Lean/rich switching is used to minimize H_2S during desulfurization

Source: Toyota, Vienna Motorsymposium 4/02

MECA

Improvements in System Integration

New Integrated DPF / NOx Adsorber Is Described; Achieves 80% Reductions in PM and NOx

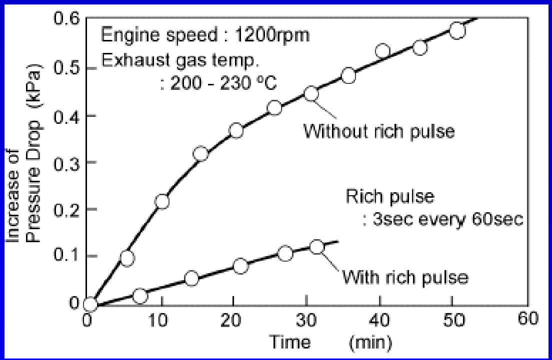


The principle of combination diesel particulate/NOx reduction system. PM is oxidized in both lean and rich conditions.

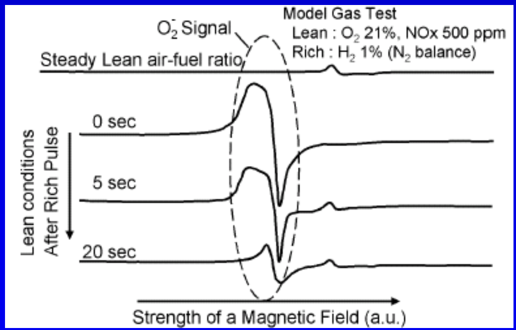
$NO + 1/2\ O_2 = NO_2$

$BaO + 2NO_2 + 1/2\ O_2 = Ba(NO_3)_2$

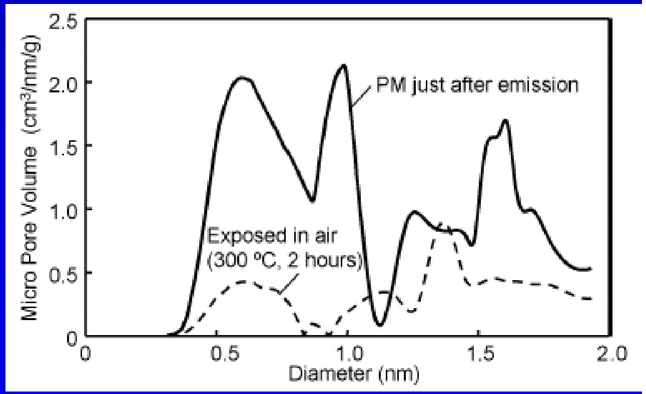
"$1/2O_2$" is the "active oxygen", and is generated on the forward and reverse reactions



Periodic rich pulse causes PM to oxidize



Active oxygen pulse is strongest right after rich pulse

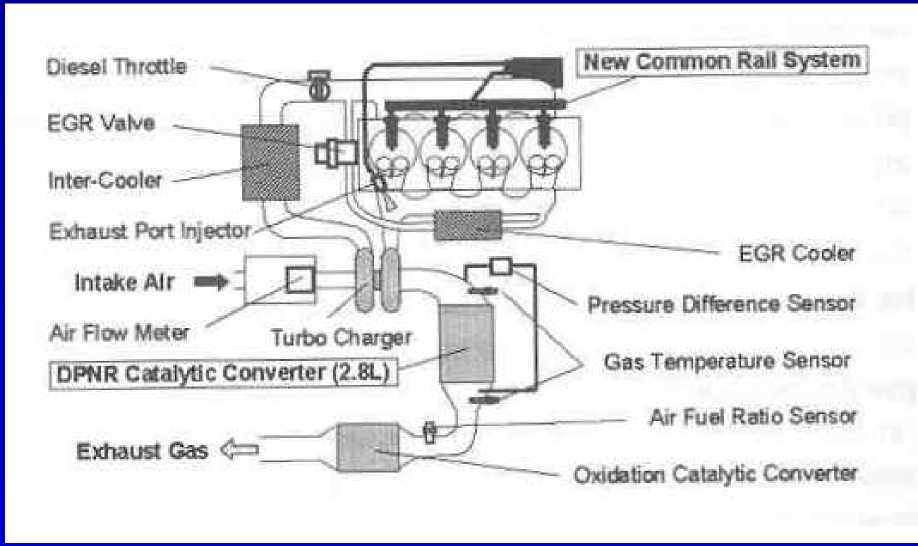


Fresh soot has more micropores and higher activity than older soot

Source: Toyota SAE 2002-01-0957

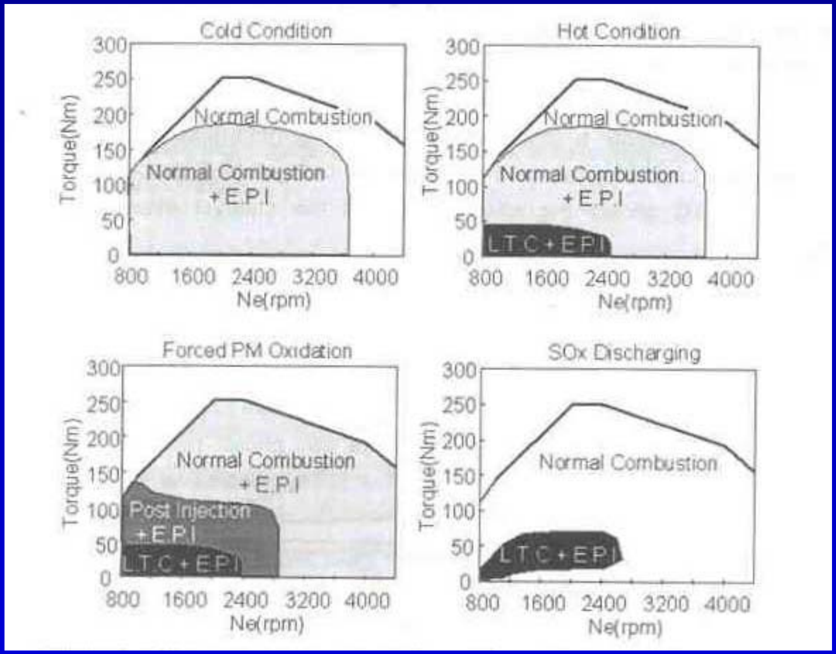
MECA

In Light-Duty Sector, Integration of Engine Management and NOx Adsorber Is Getting Tighter to Optimize Overall Performance



LTC: adv. EGR control, injection timing, and throttling are used to drop PM and NOx and increase HC and T (+50C°); presumed to be rich HCCI

EPI: auxiliary fuel injection helps richness and drivability.



System Control under Different Operating Conditions (LTC: Low Temperature Combustion. EPI: Exhaust Port Injection)

Source: Toyota, Vienna Motorsymposium 4/02

Emission Control Technology Is Advancing while Engine Technologies Are Reducing NOx and Improving Effectiveness

- Engine improvements enhance adsorber performance
  - Improved EGR, fuel injection equipment, engine management, and new engine hardware
  - Better heat and flow management
- Low-temperature emission control management is improving
  - Catalyst, VVT, HCCI, cylinder cut-off
- NOx trap regeneration is aided by ability to run torque neutral transitions
- To aid hot and rich desulfation, engine components are being upgraded to withstand higher temp
  - Auxiliary fuel injectors are an option

NOx adsorber technology, coupled with sophisticated engine control, is on track to achieve emissions goals

More Progress Is on the Horizon...

- Continuously Develop Improved Catalysts
  - Combine low and high temperature performance attributes
  - More sulfur resistant NOx adsorbers
  - Improve durability to PM and desulfation regeneration modes
- Work with OEMs to Refine Control Strategies
  - Rich transient optimization to take advantage of catalyst properties
  - Exhaust temperature control to keep within optimum window
  - Engine lab programs with OEMs to increase this year

More Progress Is on the Horizon...

- Work with NOx Sensor Suppliers
  - Help catalyst establish OBD measurements
- Combine NOx Adsorber with Diesel Particulate Filter to Obtain Synergistic PM and NOx Control
  - Integrated PM filter/NOx adsorber combinations add rather than detract from one another
  - Programs initiated with OEMs

Conclusion

- Our Industry Concurs with the Conclusions of EPA's *Highway Diesel Progress Review*
  - The necessary investments are being made by the emission control industry to develop and commercialize the diesel exhaust emission control technologies that will be needed to help meet the 2007 HDE standards
  - The technological progress in developing and commercializing diesel particulate filter and NOx adsorber technology is on track to be ready in 2007 and 2010